THE PHYSICAL SOCIETY OF LONDON.

PROCEEDINGS.

VOLUME XXXIV.—PART II.

FEBRUARY 15, 1922.

Price to Non-Fellows, **6s.** *net, post free* **6/3.**

Annual Subscription, **30/-** *post free, payable in advance.*

Published Bi-Monthly from December to August.

LONDON:
FLEETWAY PRESS, LTD.,
3-9, DANE STREET, HIGH HOLBORN, W.C.1.

1922.

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VII. *On the Average Range of β-Rays in Different Metals.* *By* G. A. SUTHERLAND, *M.A.*, *and* L. H. CLARK, *B.Sc.*

ABSTRACT.

Measurements of the range of β-particles in various metals were made in 1910 by Prof. W. H. BRAGG. The present Paper relates to a repetition of these measurements, employing 3 grams of radium bromide. The method consists in determining the ionisation in a lead chamber exposed to very penetrating γ-radiation, when various linings are inserted in it. The quantitative results obtained earlier are substantially confirmed by the present investigation.

THE present Paper owes its origin to a suggestion of Professor Sir W. H. Bragg that it would be worth while repeating some of his earlier γ-ray determinations with the larger quantities of radium now available. In particular the redetermination of the average range of β-rays in different substances seemed of special value. By the courtesy of the authorities at the Middlesex Hospital access to a considerable quantity of radium was arranged for the purpose of this investigation.

The theory of the method followed has already been explained by W. H. Bragg,* and it seems unnecessary to repeat it here. The experiments consisted in measuring the ionisation in a lead chamber, exposed to very penetrating gamma radiation, when different linings were inserted into it.

The apparatus consisted of a cylindrical ionisation chamber placed in the beam of gamma radiation from a brass box containing 3 grams of radium bromide. The source *S* consisted of a number of small glass tubes containing the radium salt, which were distributed uniformly over a disc of 11·7 cm. diameter and were screened by a lead disc 2 cm. thick. The tubes with their lead shield were contained in a flat, cylindrical brass box 13 cm. in diameter and 4 cm. deep. The ionisation within the chamber *C* was measured by means of the electroscope *E*, which was very efficiently shielded from direct radiation by placing the radium container in a lead cubical block of 52 cm. side.

The diagram shows the apparatus with the ionisation chamber in the end-on position and gives the dimensions of the latter, which was made of lead 0·49 cm. thick. It was arranged that the ionisation chamber could be disconnected from the electroscope and by making one of its ends removable the insertion of various metal linings into the chamber was easily effected.

It will be observed that the ionisation chamber is arranged unsymmetrically with respect to the radio-active source *S* in order to prevent considerable ionisation taking place within the stem connecting the chamber to the electroscope. As it was, 5 per cent. of the total ionisation as given by the electroscope was due to that occurring in the stem.

The experiments of Bragg for the end-on position of the lead chamber have been repeated for linings of tin, zinc, iron and aluminium. In addition a lining of copper was used.

Table I. shows the results obtained for the different linings when the ionisation chamber was in the one case in the end-on and in the other in the broadside-on positions with respect to the radium container. The second column gives the mean thickness of the lining and the figures in the third and fourth columns are corrected for differences in volume and for differences in the strengths of the γ-rays due to the

* Phil. Mag., Sept. (1910).

differing absorptions by the various linings. For comparison, the figures in the fifth column are taken from the Paper already mentioned,* and were obtained by using a source of only 5 milligrams of radium bromide. The agreement between the earlier and later figures is striking.

TABLE I.

Metal.	Mean Thickness of lining in cm.	Ionisation in *C* when broadside-on.	Ionisation in *C* when end-on.	The Earlier Values.
Lead	0·49	100	100	100
Tin.....	0·16	67·2	68·2	68
Zinc	0·21 0·35 0·42	55·3, 54·4	52·5, 53·6 54 54·9	55
Copper	0·19 0·25 0·31	55: 55·5	57·3, 57·9 57·1 56·5	...
Iron	0·25 0·155	55·3	56·6	54
Aluminium ...	0·26 0·21	49·6	48·2	49

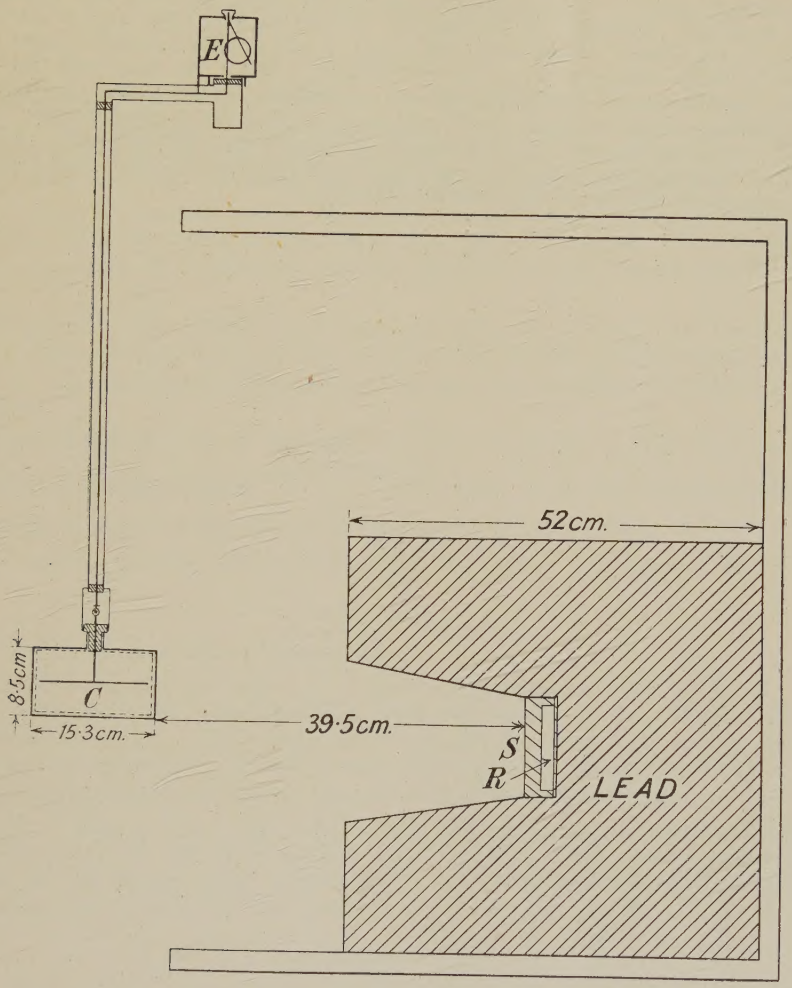
The theory of the experiment requires that the relative figures for the different linings should be independent of the thickness of the lining, provided that the initial thickness is sufficient to prevent the passage of β-rays originating elsewhere. The figures obtained for different thicknesses of the copper and of the zinc linings show that for these two metals, at least, this is approximately the case. The other metals were not subjected to a similar test.

TABLE II.

Metal.	Broadside-on. Ionisation, I.	End-on. Ionisation, II.	I./II.
Lead	268	202	1·33
Tin.....	140	107	1·31
Zinc	118	84·6	1·39
Copper.....	115	90·2	1·28
Iron	105	81	1·30
Aluminium	103	75	1·37

* Loc. cit.

Table II. gives the values of the ionisation obtained for the various linings when the ionisation chamber was (*a*) in the end-on position and (*b*) in the broadside-on position. The last column gives the ratios of the ionisations for one and the same



lining for the two positions. It will be seen that this ratio is approximately the same for all linings chosen, which is in agreement with theory.

In conclusion, we wish to express our thanks to Prof. Sir W. H. Bragg and Prof. S. Russ for their kind help and suggestions.

DISCUSSION.

Sir W. H. BRAGG: I should like to explain the object of the previous researches to which Mr. Sutherland has referred in his extremely interesting Paper. When an electron meets an atom there are two changes which may take place—changes, namely, in its speed and in its direction—and it was my object to measure their effects separately. In dealing with α-particles the separation of these two factors is comparatively easy, because in this case changes of direction

are rare—although it is by investigating those changes of direction, when they do occur, that Rutherford has been able to find out so much about the atom. But suppose, for instance, that you put screens of various thicknesses in the path of a pencil of β-rays, and measure the so-called "absorption coefficient." The effects of the two factors—change of speed and change of direction—are compounded, and it is very difficult to interpret your result, or to say what it really is that has been measured. However, by adopting the conception of the *total range* of a β-particle—the length, that is, which its total path would have if it were straightened out—we get the result that given a certain number of β-particles per gramme of metal, the density of their tracks is independent of the amount of twisting and turning which they exhibit. The idea may be illustrated by taking a square of paper and drawing on it a zigzag line of given length. Whatever shape you may give to the line, the total quantity of ink you use will be the same. I personally am much indebted to Messrs. Sutherland and Clark for having seized the opportunity of repeating these measurements with such a large quantity of radium.

VIII. *On the Sensitivity of Ballistic Galvanometers.* By Professor Ernest Wilson.

Received August 20, 1921.

(Communicated by D. Owen, D.Sc.)

ABSTRACT.

(1) The Paper deals with a method whereby the effects due to excessive *damping in moving coil galvanometers* are largely diminished. The circuit is opened after an interval of time which is small compared with the periodic time of the instrument. This gives rise to an increased first deflection, and consequently, greater sensitivity.

(2) *Analytical Treatment.*—The theory indicates the greater sensitiveness of the galvanometer when the method described in the Paper is employed. For the measure of *Quantity* it is equally as satisfactory and more simple in its application than the ordinary method.

(i.) *Constant Time Interval of Closing the Secondary Cricuit and Constant Total Resistance.*—The values of the Quantity of Electricity are directly proportional to the first deflection. The experiments demonstrate that this is true within the limits of error in observation.

(ii.) *Variable Resistance of Secondary Circuit.*—It is shown that the Quantity of Electricity, Q, is proportional to $\frac{(\text{deflection})}{R}\varepsilon^{\alpha t_1/R}$ where R is the total resistance, t_1 the time interval of closure of the secondary circuit, and α is a constant.

(iii.) *Constant Quantity and Variable Total Resistance.*—The observed first deflection is equal to

$$\beta/R\varepsilon^{\alpha t_1/R},$$

where α and β are instrumental constants.

(3) *Experimental Confirmation of Theory.*—Experiments were made *to test the accuracy of the theory*, the time interval t_1 being determined (*a*) by a weight falling with uniform velocity, which strikes two levers in turn, the first lever interrupting the primary coil of a mutual inductance, and the second interrupting the secondary circuit; and (*b*) by a freely falling weight released by the operation of the primary switch.

(4) *The Testing of Iron.*—The method has been applied to the testing of iron when the magnetic force, H, was of the order 7×10^{-6} C.G.S., and the corresponding magnetic induction, B, was of the order $1{,}000\times10^{-6}$ C.G.S. The gain in sensitivity has been fruitful of greater accuracy in the results.

Introductory.

When a galvanometer of the moving-coil type is employed ballistically for the measurement of a small quantity of electricity in a secondary coil connected to the instrument, and when in an extreme case the resistance of the circuit is small, the damping effect in the instrument may be considerable.

Suppose that the secondary circuit is opened after an interval of time at least equal to and coincident with the time of duration of the transient current, but small compared with the periodic time of the galvanometer, the first deflection will be increased and greater sensitivity will be secured. The necessary analysis underlying the action of the galvanometer under the two different conditions of damping is now given; it is, of course, in its main essentials similar to that worked out in general terms by Lord Kelvin in the theory of the siphon recorder. But it does not appear that this method of securing greater sensitivity in the galvanometer has

been adopted hitherto.* The analytical treatment is accompanied by the results of experiment.

THEORETICAL.

Let R be the resistance of the swinging coil of a ballistic galvanometer, and A its area of cross section. When swinging with deflection θ in a magnetic field of intensity H, an E.M.F. $HA\dot{\theta}$ is induced in the coil. If we take no account of its self-induction—as is evidently justifiable in the majority of cases, and especially so in the present instrument—the induced current is $i=HA\dot{\theta}/R$, where R is the resistance of the coil and the remainder of its circuit. Energy is dissipated by induction at a rate given by

$$\tfrac{1}{2}Ri^2=\tfrac{1}{2}\cdot\frac{H^2A^2\dot{\theta}^2}{R}$$

If mk^2 is the moment of inertia of the coil, and κ a decrement factor, the equation of motion of the coil becomes

$$mk^2\ddot{\theta}+\left(\kappa+\frac{H^2A^2}{R}\right)\dot{\theta}+\mu\theta=0$$

where μ is a constant of the instrument, related to its *free* period T by the equation

$$\frac{\mu}{mk^2}=\frac{4\pi^2}{T^2}$$

Writing $\kappa/mk^2=p, \quad \kappa/mk^2+H^2A^2/Rmk^2=q$

for brevity, we have

$$\ddot{\theta}+q\dot{\theta}+\frac{4\pi^2}{T^2}\theta=0$$

This equation is valid while the key is kept closed, so that the induced current continues to flow through the coil of the instrument. During the period in which the key is kept open, q is replaced by p, the inductive agencies not being then in operation.

While the key is down, if we write

$$D=-\frac{q}{2}\pm\tfrac{1}{2}\sqrt{q^2-\frac{16\pi^2}{T^2}}=-\frac{q}{2}\pm i\rho \text{ (say)}$$

$$\theta=A\varepsilon^{-qt/2}\sin\rho t$$

making θ vanish with t. Thus

$$(\dot{\theta})_{t=0}=A\rho.$$

For $(\dot{\theta})_{t=0}$, the initial angular velocity of the needle, we may use the usual

* Since the reading of this Paper my attention has been called to a communication by B. Wwedensky in the current number of the Annalen der Physik (Nov., 1921), who, in addition to using the method, refers to a Paper by M. Gildemeister (Ann. d. Physik, Vol. XXIII., p. 401, 1907), in which it is also described. I wish to take this opportunity of acknowledging these publications. I should like to add that the authors have not made a special study of the instrument itself as in the present communication.

relation connecting it with the quantity Q of electricity to be measured, and if G is the usual constant of the ballistic galvanometer,

$$(\dot{\theta})_{t=0}=\frac{MGQ}{mk^2}=A\rho$$

Thus
$$\theta=\frac{MGQ}{mk^2\rho}\varepsilon^{-qt/2}\sin\rho t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

during the initial period when the key is kept down. Suppose that the key is kept down for an interval t_1—afterwards made small in comparison with the period T of the instrument. Then at the end of this interval t_1, the values of θ and $\dot{\theta}$, say θ_1, $\dot{\theta}_1$, at $t=t_1$ are derived from (1), and are the initial values for the second interval with the key open, and q equal to p. In this second interval, the general solution of the differential equation is

$$\theta=\varepsilon^{-pt/2}\left\{A\cos\frac{2\pi t}{T}+B\sin\frac{2\pi t}{T}\right\}$$

Moreover, p is very small, being the *natural* decrement of the instrument, not involving the inductive agencies.

Introducing now the consideration that t_1 is very small in comparison with T, the natural period of the instrument, we may write with a sufficient approximation

$$(\theta)_{t=t_1}=A+\frac{2\pi t_1}{T}B$$

$$(\dot{\theta})_{t=t_1}=\frac{2\pi B}{T}\varepsilon^{-pt_1/2}$$

$$\sin\rho t_1=\rho t_1$$

Thus
$$A+\frac{2\pi t_1}{T}B=\frac{MGQ}{mk^2}t_1\varepsilon^{-qt_1/2}$$

$$\frac{2\pi B}{T}=\frac{MGQ}{mk^2}\varepsilon^{-qt_1/2}$$

using the values of $(\theta,\dot{\theta})_{t=t_1}$ derived from (1) directly, A being small in comparison with B.

Accordingly, at time t on the second interval—the zero of time being the beginning of the first interval—we have to a sufficient order of accuracy

$$\theta=\frac{T}{2\pi}\cdot\frac{MGQ}{mk^2}\cos\frac{2\pi t}{T}\varepsilon^{-pt/2-qt_1/2}$$

showing the natural decrement. The effect of the first interval is, to this order, effectively confined to the exponential factor $\varepsilon^{-qt_1/2}$. The maximum of θ occurs when $t=\frac{1}{4}T$ as usual, and is given by

$$(\theta)_{\max.}=\frac{T}{2\pi}\cdot\frac{MGQ}{mk^2}\varepsilon^{-pT/8-qt_1/2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If the key had been depressed throughout, we should have obtained from (1)

$$\theta=\frac{MGQ}{mk^2}\left\{\frac{4\pi^2}{T^2}-\frac{q^2}{4}\right\}^{-\frac{1}{2}}\varepsilon^{-qT/8} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The wide difference in the values of p and q in (2) and (3) indicates the much greater degree of sensitiveness of the galvanometer in the former case. In other respects the formula (2) indicates that, as a measure of Q the method is equally satisfactory, and if t_1 is very small and is maintained constant, together with the resistance R, while measuring different values of Q, such values are directly proportional to the first deflections. The formula is also of great simplicity in its application, as compared with (3). Effectively, the natural decrement operates during the greater part of the first swing.

The effect of a varying resistance in the circuit of the coil is of some interest. For fairly small resistance, we may write

$$q=\frac{H^2A^2}{Rmk^2}=\alpha/R \text{ (say)}$$

or Q varies inversely as the resistance, α being a constant. Then

$$Q \propto \frac{(\text{deflection})}{R}\, \varepsilon^{\alpha t_1/R}$$

In measuring the same value of Q—or the same magnetic induction in an actual

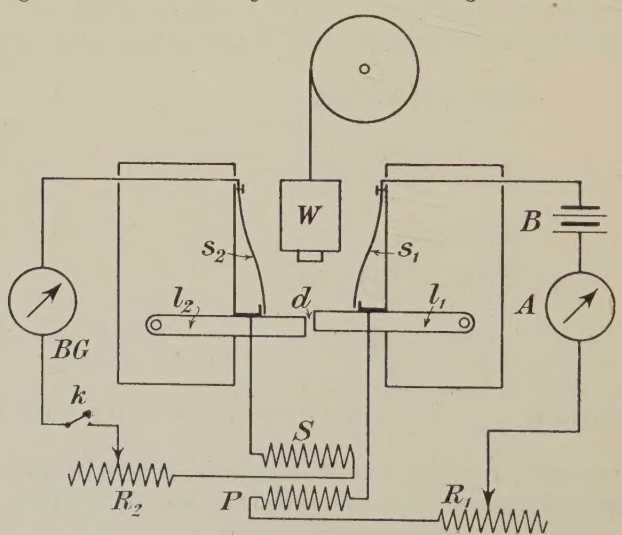


FIG. 1.—DIAGRAM OF EXPERIMENTAL ARRANGEMENT.

experiment—with varying resistances by this method, we should find that the law connecting the deflection with the interval t_1 of closing the circuit, and the resistance R of coil and circuit, is of the form

$$\text{Deflection}=\frac{\beta}{R}\, \varepsilon^{\alpha t_1/R}$$

where α and β are instrumental constants. The verification of this formula supplies a good test of the performance of an instrument, and of the accuracy with which experimental conditions involving a given value of the measured magnetic induction, can be reproduced. It is evident that considerable care is required, and that a

determination of α and β is necessary, before deflections obtained with low values of R can be interpreted.

Experimental Verification of the Theory.

In Fig. 1 P and S represent the primary and secondary windings of an air-core transformer whose mutual inductance was 0·067 henry. The current in the primary circuit is supplied by a battery, B, and measured by an ampere-meter A, and its magnitude is varied by an adjustable resistance R_1. Two levers, l_1 l_2, are held horizontally by contact pressure due to springs S_1 S_2. The primary circuit is interrupted by a falling weight W on striking the lever l_1, and after an interval of time (t_1) the secondary circuit is interrupted on the weight striking the lever l_2. The time-interval t_1 is determined by the difference in level d between the two levers l_1 l_2, and the velocity of the falling weight W. To check the accuracy of the small values of t_1, determined from measurements of d and the velocity of W, the proportion of charge lost by a condenser through a high resistance during the time t_1 was determined by a quadrant electrometer, and hence the value of t_1 was found. The weight was supported by a cord wound on a pulley, which was geared to a train of wheels terminating in a rapidly rotating vane. Thus the velocity was kept constant by air friction over a considerable distance, and its value was accurately determined. The difference of level d was capable of adjustment by raising or lowering the framework supporting the lever l_2.

The ballistic galvanometer BG was of the D'Arsonval type, and had a resistance of 467 ohms. The resistance of the secondary coil S was 48 ohms. A variable resistance R_2 and key k were included in the secondary circuit. The scale used with the galvanometer had $\frac{1}{2}$ mm. divisions, and was at a distance 1,340 mm. from the mirror. The constants of the instrument were: Periodic time, 8 seconds; amperes per scale-division steady deflection, $1{\cdot}5 \times 10^{-9}$; coulombs per scale-division, $1{\cdot}91 \times 10^{-9}$; decrement factor on open circuit, 1·03.

(*a*) Time of Contact t_1 Constant.

Experiments were first made to verify the prediction of theory that for a given value of the time t_1 and for a given total resistance the first deflection θ is proportional to the quantity of electricity Q. Two sets of curves are given in Figs. 2 and 3, in which the primary current in arbitrary units is plotted horizontally and the deflections vertically; they indicate an exact agreement with theory. In the first set (Fig. 2) the value of t_1 is 0·094 second, and it is 0·397 in the case of Fig. 3.

(*b*) Time of Contact t_1 Varied.

The second set of experiments consisted in keeping the primary current constant, and varying the resistance in the secondary circuit (R_2) for given intervals of time t_1. The deflections thus obtained are given in Table I., and Fig. 4 is a graph in which for a given total resistance the time t_1 is plotted horizontally and the first deflections vertically. When the total resistance is 515 ohms the deflections increase rapidly as the time t_1 diminishes, and after rising to a maximum they would fall to zero when $t_1 = 0$. If the time t_1 had the value 0·1 second in actual working, the sensibility on the first deflection would be increased 1·8 fold as compared with the usual method of keeping the secondary circuit permanently

closed ; and it would be increased 3·3 fold if, as is sometimes the case, the sum of the first and second deflections is employed.

TABLE I.

Time of Contact t_1 in seconds	$R=515$ $Q=1\cdot52\times10^{-6}$.		$R=1520$ $Q=0\cdot515\times10^{-6}$.		$R=5520$ $Q=0\cdot142\times10^{-6}$.		$R=10520$ $Q=0\cdot0745\times10^{-6}$.	
	θ_1	θ_2	θ_1	θ_2	θ_1	θ_2	θ_1	θ_2
∞	390	17	204	82	69	47	38	28
2·77	392	315	206	183	72	62	39	34
0·787	436	403	222	207	73	67	40	36
0·412	546	480	242	210	75	66	39	35
0·187	655	550	259	218	76	63	39	30
0·094	720	612	266	232	76	64	39	35

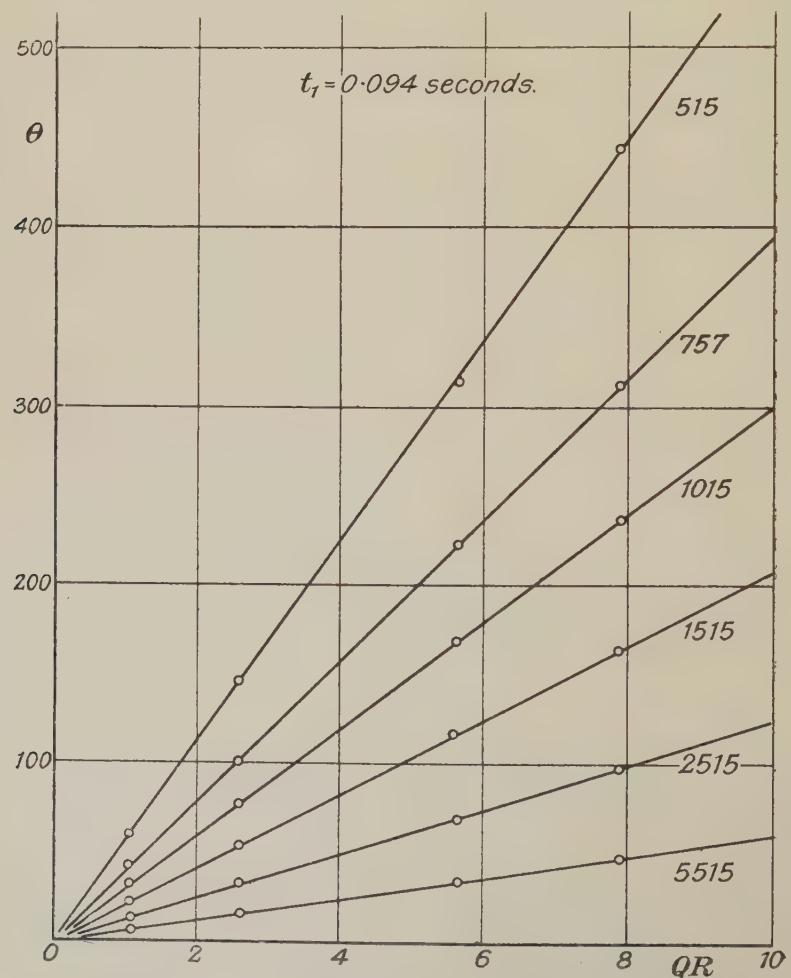


FIG. 2.—OBSERVED GALVANOMETER DEFLECTIONS—t_1 CONSTANT.

When swinging with its coil on open-circuit the decrement factor is 1·03, and this is to a near approximation true when the total resistance has the value 10,520 ohms. The calibration of the instrument with this factor gives $1{\cdot}91\times10^{-9}$ coulombs per scale division. Confining ourselves to the first deflection, now called θ_1 to distinguish it from the second deflection θ_2, the quantity discharged is $39\times1{\cdot}91\times10^{-9}=74{\cdot}5\times10^{-9}$ coulombs when R has the value 10,520 ohms.

If the primary current is kept constant then the electro-motive-force induced

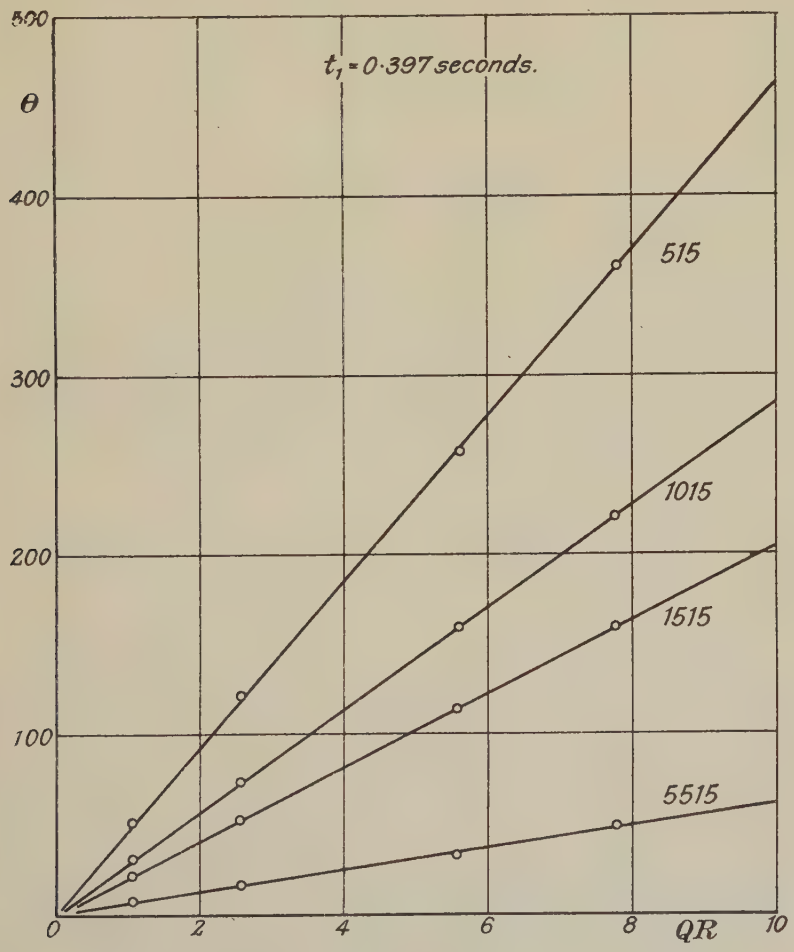


FIG. 3.—OBSERVED GALVANOMETER DEFLECTIONS—t_1 CONSTANT.

in the secondary coil is a constant, and the quantity discharged through the instrument on interrupting the primary circuit will be $10520\times74{\cdot}5\times10^{-9}/R$ coulombs for various resistances R. The theory states that the deflection θ_1 is equal to $\beta/R\varepsilon^{\alpha t_1/R}$, where α and β are instrumental constants. From the values of t_1 θ_1 and R given in Table I., the values of α and β have been obtained, and these are given in Table II. It will be seen that for values of R 515 and 1520, α varies from —403 to —730, and

for values of R 515 and 5520 the variation is from —422 to —755. This shows primarily the effect of having t_1 important in comparison with the periodic time of the instrument.

TABLE II.

Time of Contact t_1 in seconds.	R 515 and 1520.		R 515 and 5520.	
	α	β	α	β
0·094	—730	415×10^3	—755	424×10^3
0·187	—635	422×10^3	—658	414×10^3
0·412	—510	425×10^3	—535	431×10^3
0·787	—403	422×10^3	—422	427×10^3
		1684		1696
		Mean 422×10^3		Mean 424×10^3

If the galvanometer coil were free to move without retarding forces, one would expect the deflection θ_1 to vary strictly as the quantity Q. Referring again to Table I., and increasing θ_1 observed with 10,520 ohms total resistance, in the ratio of the quantities, the values of θ_1 without serious decrement have been worked out. The differences $\delta\theta_1$ between the values calculated without decrement and the observed values are given in Table III., together with the percentage diminution. When the time of contact t_1 is 0·094 second, the deviation is less than 10 per cent. with a total resistance of 515 ohms, and it falls to zero as the resistance is increased. As the time of contact is increased the percentage variation increases until it is equal to 50 with 515 ohms total resistance.

TABLE III.

Time of Contact t_1 in seconds.	$R=515$		$R=1520$		$R=5520$	
	$\delta\theta_1$	Per cent.	$\delta\theta_1$	Per cent.	$\delta\theta_1$	Per cent
∞	405	51	66	24·4	7	9·2
2·77	403	50·5	64	23·7	4	5·26
0·787	359	45	48	17·8	3	3·95
0·412	249	31·3	28	10·3	1	1·32
0·187	140	17·6	11	4·07	0	0
0·094	75	9·45	4	1·5	0	0

When working with this method it is necessary to be quite certain that the time of contact t_1 is sufficiently long to allow of the complete change in the magnetism when measurements of permeability are in question. This can be checked by taking deflections with a high constant resistance in circuit for various times of contact. The deflections should be equal until t_1 reaches the minimum value below which it should not be allowed to go. Alternatively with low total resistance the time t_1 should be adjusted to give a maximum deflection.

APPLICATION OF THE METHOD TO THE TESTING OF IRON.

When the ballistic galvanometer is used in the testing of iron a switch is employed to reverse the primary current. To break the secondary circuit at known intervals of time after reversal, use has been made of a freely falling weight, which is released by the reverser at the instant when reversal is complete. On falling through a

given distance the weight strikes a lever and severs the secondary circuit. The arrangement consists of a vertical tube, which acts as a guide for a small cylinder of brass. Initially the cylinder is supported in its position at the top of the tube by a wire which is threaded through a small hole in the cylinder, and which is attached to the reverser. The wire is so adjusted in length that at the instant the primary current is reversed the cylinder is released and falls as above stated. The time interval t_1 is varied by varying the distance of fall.

Application.

It only remains to describe experiments which were made with a cylinder built up of transformer iron stampings, the object being to discover if the permeability reaches a constant value when very small changes of the magnetic induction are in question. Previous experiments with these stampings indicated that between the

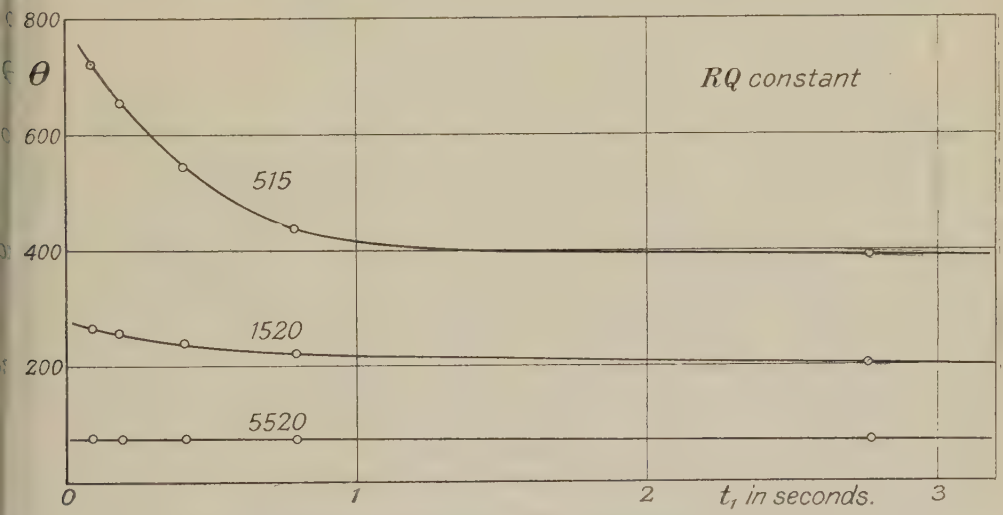


Fig. 4.—Observed Galvanometer Deflections—*RQ* Constant.

limits of the magnetic force H 0·0356 and 0·000073 the permeability varied from 172 to 148.*

The cylinder had a volume of 23,440 cubic cm., and the average thickness of the stampings was 0·0613 cm. Each stamping had internal and external diameters 30·5 and 40·6 cm. respectively, and the effective cross-section of the cylinder was 210 sq. cm. For use with the instrument used in the foregoing experiments it was decided to wind on three layers of insulated copper wire for the secondary coil, and calculation showed that the ratio of turns on the three layers to the resistance of the coil and galvanometer had a maximum value when the wire, which was insulated with a double layer of cotton, had a diameter of 0·061 cm.

At the time of making the present experiments only two of the layers had been wound, and the total turns were 1,838, and the resistance 102 ohms ; the results are not intended to be more than preliminary or tentative. The primary winding was

* Proc. Roy. Soc., A. Vol. XCIII., 1917, p. 409.

wound over the secondary coil, and consisted of copper foil 7·5 cm. wide, and the total turns on the single layer were 16. The whole surface of the cylinder was covered by the primary coil, and to prevent overlapping the width of the copper foil had to be reduced on the inside surface of the cylinder.

The deflections were observed when the key in the secondary circuit was continuously closed, and when it was opened 0·2 second after reversal had been completed. In order to eliminate the zero reading of the instrument the sum of the first and second deflections (θ_1 and θ_2) have been taken,

TABLE IV.

H 10^{-6}.	$\theta_1+\theta_2$		B 10^{-6}	μ
	$t_1=\infty$	$t_1=0·2$		
17·1	9·5	29·5	2480	145
11·4	6·5	19·0	1600	140
8·55	5·5	14·0	1180	138
6·84	3·5	11·1	935	137

and these are set out in Table IV. From the data supplied in Table I. it has been estimated that when the total resistance is 569 ohms, and when $t_1=0·2$ second, the value of $\theta_1+\theta_2$ must be multiplied by the factor 1·20. Assuming this factor in conjunction with the ordinary constants the values of the magnetic induction B have been found, and hence the permeability μ. It will be seen that the values of $\theta_1+\theta_2$ when $t_1=\infty$ are very small, whereas when $t_1=0·2$ second the values are roughly three-fold, and can be read to a greater degree of accuracy. The experiments are being continued with the completed secondary circuit, but so far as the present experiments go it would appear that when the magnetic force varies from 17×10^{-6} to $6·84\times10^{-6}$ C.G.S. units the permeability is still variable.

DISCUSSION.

DR. MARSH: I have been greatly interested in Prof. Wilson's Paper on a method of increasing the sensitivity of a moving coil ballistic galvanometer, and the more so as I have been employing a very similar method for several years. A special form of key was used, by depressing which the primary current was closed, while further pressure released a spring which opened the galvanometer circuit. The time interval between the closing of the one and the opening of the other could be varied at will. When this interval is too short, the inductive discharge through the secondary is not complete, and the galvanometer throw is too small; if the interval is too long, the galvanometer coil moves sensibly from its initial position, and the electromagnetic damping reduces the throw. The *maximum* throw is taken (quickly obtained after a little practice), the throw being corrected subsequently for air damping in the ordinary way. In the "reversals" method the ordinary form of commutator was used, and the key described was employed solely to break the secondary circuit. It would appear that if a *definite* time interval is to be employed, as in Prof. Wilson's method, then it is of the highest importance that such an interval be measured with considerable accuracy. With regard to the graphs plotted in Figs. 2 and 3, they do not appear to me to be a verification of Prof. Wilson's theory of the damping effect; for reference to equation (2) shows that for a given t_1, the exponential factor is constant, and consequently the factor embodying his results disappears when ratios are taken. A better test of the theory would be to keep Q constant and determine the value of $\theta_{max.}$ for different values of t_1. Equation (2) would then suggest the relation $\theta_{max.} \propto \varepsilon^{-qt_1/2}$, the other factors being constant. On plotting the values of log θ_1 against t_1 (first and second columns of Table I.), the graph is very different from a straight line.

DR. RUSSELL: I have been much interested in the author's ingenious demonstration of the principle described in his Paper, and particularly by the results he has obtained in connection

with the permeability of iron. It is too often assumed that the result given by Lord Rayleigh long ago, namely, that the permeability is constant for very small values of H, is correct beyond question. The author's investigation seems to throw doubt on this assumption, and the question is one which ought to be settled.

Mr. T. SMITH: I should like to ask the author if he can give us any information as to the physical significance and the importance of the shape of the permeability curve in the neighbourhood of the origin, to which reference has been made in the Paper and by the last speaker.

Mr. C. C. PATERSON remarked that the question touched upon by the last two speakers was of great importance in telephone and high-frequency problems.

Dr. D. OWEN enquired whether the author had tried the measurement of small changes of magnetic flux, using a galvanometer of the moving-needle type, such as the Broca. Doubtless magnetic shielding would be involved, and his experiences in that direction would be of interest.

Prof. WILSON, in reply, said: I am much interested to learn from Dr. Marsh that he has been employing the method of obtaining increased sensitivity by breaking the current of a ballistic galvanometer attached to the secondary coil of an iron-cored transformer, and in reply to his remarks, I should like to state that the experiments described in the Paper were largely carried out with a view to their application in the testing of iron in fairly large masses. In the experiments at the end of the Paper, I was concerned with the total change of magnetism in a very large specimen, and not the instantaneous effect. I found that a time of about 0·2 of a second was necessary in order to obtain a maximum deflection on the instrument, and this was the time actually used. The figures given in Table II. were intended to show that, provided I kept this time of contact constant, I should be safe in assuming the observed deflections to be strictly proportional to the change of magnetism. I have not obtained the true value of α directly from the instrument itself, but this could be done if necessary. The variable value of this constant I attribute to the higher approximations which were made in the analysis leading up to the formula given in the abstract. It is explicitly stated that the time of contact must be very small in comparison with the periodic time of the instrument, if the formula is to be capable of general application; and this is clearly not the case in my experiment. When the value of the time of closure t_1 is allowed to vary through wide limits it would be necessary to go back to the fundamental formulæ involving no such approximations.

The remarks of Dr. Russell are exceedingly interesting to me, as I have felt for many years that the results of Lord Rayleigh's experiments merit further investigation. The constancy or not of magnetic permeability in iron at very low forces is of great importance at the present time, and it is worthy of note that ballistic galvanometer tests do not agree with those of Lord Rayleigh, who used the magnetometer. If I might make the suggestion, I feel that Lord Rayleigh's experiments could be repeated with advantage in order to discover if there was anything in his instrumentation which might possibly lead to other results.

Mr. T. Smith's remark with regard to the shape of the hysteresis loops when very low values of magnetic induction are in question, is an interesting one. It is well known now that these loops do not in any way resemble the ordinary hysteresis loops obtained in magnetic testing, as they ultimately resolve themselves into two parallel straight lines enclosing a very small and diminishing area.

Mr. Paterson quite rightly emphasises the importance of the subject in telephonic and high-frequency problems.

In reply to Dr. Owen, I may say that I have not worked with a Broca galvanometer, but I contemplate doing so.

Since the reading of my Paper, Professor Howe has called my attention to the current number of the "Annalen der Physik" in which a Paper by M. Wwedensky deals with the problem of opening the ballistic galvanometer circuit with a view to increasing its sensitivity. He refers to a Paper by M. Gildemeister (Annalen der Physik, 1907, XXIII., p. 405), who used this self-same method, and deserves all credit for his early publication. Gildemeister was concerned with the instantaneous change of magnetism which occurred in very fine iron wires at an early stage (under a thousandth of a second) after the breaking of a magnetising current. He used a Helmholtz pendulum, making the secondary circuit after a very small interval of time, and breaking it after a further very small interval of time, for the purpose of obtaining increased sensitivity in the galvanometer.

IX. *On the Determination of the Damping Decrement of a Tuning Fork.* *By* R. Ll. Jones, *M.A.*

Received October 10, 1921.

1. In Proc. Phys. Soc., Vol. XXXI., p. 87, 1919, A. Campbell describes a method of determining the damping decrement of a tuning fork. The vibrating prong of the fork causes the induction through a coil fixed near it to vary. An E.M.F. is thereby induced in the coil. The coil is connected to a sensitive vibration galvanometer tuned to the frequency of the fork. As the fork vibration dies down the galvanometer deflection falls off similarly. It is assumed that the amplitudes of the galvanometer vibrations are closely proportional to those of the fork, and hence that their rates of decay are the same. If θ_0 and θ_1 be the amplitudes of the galvanometer vibrations at times $t=o$ and $t=t_1$ respectively, the decrement c is given by

$$c=\frac{1}{t_1}\log_e\left(\frac{\theta_0}{\theta_1}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It is suggested* that the relation between the vibrations of the galvanometer and the fork requires investigation, and the theory of the method does not appear to have been considered in detail. In this Paper the motion of the vibration galvanometer, when the E.M.F. in its circuit is of the form $E_1e^{-ct}\cos pt$, will be first given, and it will be seen that in this simplest case the decrement of the galvanometer vibration is equal to the decrement of the E.M.F. to which the galvanometer is tuned. The E.M.F. induced in the circuit by the fork will then be evaluated, and its harmonic components and their decrements indicated. The conditions necessary in order to obtain the true decrement of the fork by the method will follow.

2. Let E be the impressed E.M.F., i_1 the current in the circuit, and θ the deflection of the galvanometer at a time t. The equation of motion of the galvanometer coil is

$$\alpha\ddot{\theta}+\beta\dot{\theta}+\gamma\theta=HA\,.\,i_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where H is the strength of the field in which the galvanometer coil moves and A is the effective area of the coil.

If r be the total resistance of the circuit, the current is given by

$$i_1=\frac{E-HA\,.\,\dot{\theta}}{r}$$

Substituting in (2) we get

$$\alpha\ddot{\theta}+\left(\beta+\frac{H^2A^2}{r}\right)\dot{\theta}+\gamma\theta=\frac{HA}{r}\,.\,E$$

or

$$\ddot{\theta}+2\lambda\dot{\theta}+n^2\theta=g\,.\,E \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Writing E_1e^{iqt} for E where E_1 is constant and $i=\sqrt{-1}$, the forced vibration is given by

$$\theta=gE_1\frac{e^{iqt}}{n^2-q^2+2i\,.\,\lambda q} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Let $q=p+ic$ where p and c are real.

* Campbell, loc. cit.

Substituting this for q in (4), the real part will give the forced vibration due to an impressed E.M.F., $E_1e^{-ct}\cos pt$.

Thus

$$\theta=\frac{gE_1}{R}e^{-ct}\cos(pt-\chi)$$

where

$$R^2=(n^2-p^2-2\lambda c+c^2)^2+4p^2(\lambda-c)^2 \text{ and } \tan\chi=\frac{2p(\lambda-c)}{n^2-p^2-2\lambda c+c^2}.$$

The complete solution of (3) is

$$\theta=\frac{gE_1}{R}e^{-ct}\cos(pt-\chi)+Ae^{-\lambda t}\cos(\sqrt{n^2-\lambda^2}\,.\,t+B). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

3. The second term on the right-hand side of (5) is the free vibration. In order to be able to deduce c from observations of the amplitude of θ by (1) the free vibration must be got rid of. The only practical way to do this is to give λ (which is at our disposal to a certain extent) such a value that this vibration dies away much more rapidly than the forced vibration—*i.e.*, λ must be greater than c. The actual value of λ with a given galvanometer in circuit can be determined by appropriate observations,* and the time required for the reduction of the free vibration to (say) 1 per cent. of its amplitude at any time can be calculated. If this interval be allowed to elapse after the galvanometer deflections, whatever be their initial magnitudes, are reduced to the compass of the scale, before observations for the deductions of c by (1) are begun, we may be sure that sufficient time has been given for the free vibrations to die away to insignificance, and that the amplitudes we are observing are due to the forced vibrations alone. If, for instance, $\lambda=1{\cdot}53$, then the interval is three seconds.

Assuming, then, that the free vibration has disappeared, the motion of the galvanometer coil will be given by the first term of (5). Tuning is effected by altering n. R is a minimum, and the tuning is exact when $n^2=p^2+2\lambda c-c^2$, or when $n=p$ practically, as c is very small compared with p in any tuning fork.

In this case $R=2p(\lambda-c)$.

Thus, when the galvanometer has been tuned to the frequency $p/2\pi$

$$\theta=\frac{gE_1}{2p(\lambda-c)}e^{-ct}\sin pt. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and the factors which determined the decay of θ and E are in this simple case the same—viz., e^{-ct}.

If, however, the value of E be

$$[E_1e^{-ct}+E_3e^{-3ct}+E_5e^{-5ct}+\ .\ .\ .\ ]\cos pt$$

where E_1, E_3, E_5, &c., are constants (*see* §6), then θ will be given by

$$\theta=\frac{g}{2p}\left[\frac{E_1}{\lambda-c}e^{-ct}+\frac{E_3}{\lambda-3c}e^{-3ct}+\frac{E_5}{\lambda-5c}e^{-5ct}+\ .\ .\ .\ \right]\sin pt$$

and the rates of decay of θ and E are not the same.

* A. Campbell, Proc. Phys. Soc., Vol. XXVI., p. 121 (1915).

4. The E.M.F. induced in the circuit by the vibrations of the fork can be evaluated as follows : Consider a magnetic pole of strength m near a circuit C in which a current i_1 is flowing. Let N be the number of lines of force due to m which pass through C, and let V be the potential energy of the system. Then

$$V=-i_1N \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Let F_y be the force on m due to unit current in C aiding any displacement δy of m. The work done during this displacement will be $i_1F_y \,.\, \delta y$. By this displacement N becomes $N+\delta N$, and the decrease in the potential energy of the system is by (7) $i_1\delta N$.

Hence $$i_1F_y\delta y=i_1\delta N$$

and $$F_y=\frac{\partial N}{\partial y}$$

Let E be the E.M.F. induced in the circuit C by the motion of m. Then

$$E=-\frac{\partial N}{\partial t}=-\frac{\partial N}{\partial y}\,.\,\dot{y}=-F_y\,.\,\dot{y} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

This expression for the E.M.F. may also be deduced by considering the power required to maintain the motion of m.* Let m be the polarised prong of a tuning fork, and y its displacement from the position of rest at a time t, and let $y=be^{-ct}\sin pt$. Its velocity is $\dot{y}=bpe^{-ct}\cos pt$.

Let F_y be the force on m due to unit current in the coil, when in the displaced position y, and in the direction of y. Then the E.M.F. induced in the circuit by the prong is

$$E=F_y\,.\,bpe^{-ct}\cos pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

If the value of F_y be the same at all positions of m in the course of a vibration, F_ybp is a constant, and the rate of decay of E in (9) is determined by the factor e^{-ct} alone, and is the same as that of the fork. Hence the value of c determined by (1) is the damping decrement of the fork.

If the initial amplitude of the fork be such that F_y varies sensibly over the range through which m moves, the rate of decay of E may depend, in the initial stages at any rate, on other factors besides e^{-ct}. This case then requires further consideration.

5. Suppose that F_y varies uniformly through the range of vibration of m. Let its value in one extreme position of m be F_0+f, and in the other F_0-f, b being the amplitude of the vibration, and F_0 the value of F_y in the position of rest. Then the value of F in the position defined by the displacement y is

$$F_y=F_0+\frac{f}{b}y=F_0+fe^{-ct}\sin pt$$

By (8)
$$E=(F_0+fe^{-ct}\sin pt)bpe^{-ct}\cos pt$$
$$=F_0bpe^{-ct}\cos pt+\tfrac{1}{2}fbpe^{-2ct}\sin 2pt \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The galvanometer is tuned to the frequency $p/2\pi$; its motion will therefore be

* Butterworth, Proc. Phys. Soc., Vol. XXVII., p. 411 (1915).

wholly due to the first term on the right hand side of (10), the effect of the second term of frequency corresponding to $2p$ being insignificant. The rate of decay of the effective term in E is determined by the factor e^{-ct} alone, and is the same as that of the fork. Hence in this case also the value of c determined by (1) is that of the fork.

6. Generally we have

$$F_y = F_0 + y \,.\, F_0' + \frac{y^2}{2} \,.\, F_0'' + \ldots\ldots \quad (11)$$

where $F_0' = \left(\frac{dF}{dy}\right)_{y=0}$, &c., and y is the displacement, and

$$E = F_y \,.\, y = \left(F_0 + y \,.\, F_0' + \frac{y^2}{2} \,.\, F_0'' + \ldots\right) \,.\, \ddot{y}.$$

The value of the first two terms has just been considered in §5. The contribution of the third term $\left(\frac{y^2}{2} F_0'' \,.\, \ddot{y}\right)$ to the value of E is

$$\tfrac{1}{2} b^2 e^{-2ct} \sin^2 pt \,.\, F_0'' \,.\, bpe^{-ct} \cos pt$$

$$= E_3 e^{-3ct} (\cos pt - \cos 3pt),$$

where $E_3 = \tfrac{1}{8} b^3 p \,.\, F_0''$.

The only part of this which is effective in influencing the value of θ is $E_3 e^{-3ct} \cos pt$, because its frequency is that to which the galvanometer is tuned. Its initial magnitude depends on b^3 and F_0'', and is generally not large. Its decrement is three times that of the principal term.

Similarly it can be shown that the 4th term of (11) makes no effective contribution to E, while the contribution of the 5th term has e^{-5ct} as a factor. Hence in the general case where E_3, E_5, &c., are appreciable, the effective value of E is given by

$$E = [E_1 e^{-ct} + E_3 e^{-3ct} + E_5 e^{-5ct} + \ldots] \cos pt \quad (12)$$

The rate of decay of this is *not* that of the fork, and as shown in §3 the rate of decay of θ in this case is different from that of E, and the fork.

The following example gives an idea of the relative values of E_1 and E_3 in (12) in a case of practical importance. The ratio $\frac{E_3}{E_1} = \frac{1}{8} b^2 \frac{F_0''}{F_0}$ and $\frac{F_0''}{F_0} = -3\frac{r^2 - 4y^2}{(r^2 + y^2)^2}$ for a coil of radius r with m at a distance y on the axis from the centre of the coil. The radius r being given, $\frac{F_0''}{F_0}$ is a maximum when $y=0$ and its value is $-\frac{3}{r^2}$. Taking $r=1$ cm. and $b=0{\cdot}1$ cm., $E_3/E_1 = -0{\cdot}004$ approx. in this case. If y be not zero E_3/E_1 is less than this; it is zero of course for $y = \frac{r}{2}$, and very nearly zero for a considerable range round this value of y. In practice the coil will have an appreciable depth and width of winding, and m will be a distributed and not a point pole as assumed above. The effect of all these factors is to diminish the ratio E_3/E_1, which is thus seen to be generally small.

7. These considerations show that the decrement determined by (1) *is* the decrement of the fork, provided the field defined by F_y and over which m moves is not very irregular. If the field varies uniformly the effect on the tuned galvanometer is the same as if the field were uniform, and its strength the mean strength of the uniformly varying field, and the decrement of the fork is correctly determined by the method in these cases. It is only when the rate of change or the slope of the field changes rapidly within the range of movement of m that anything appreciable of frequency $p/2\pi$ is contributed to E whose rate of decay is different from that of the fork. In this case the method may be said to fail. When the coil is that of an electro-magnet employed to maintain the fork in vibration, contributions such as E_3, E_5, &c., are usually very small compared with E_1. In any case their decrements being 3, 5, &c., times the decrement of the principal component their values become evanescent, while the deflection of the galvanometer is still finite. Thus by working with small amplitudes of the fork or in a field whose slope does not change or does not change rapidly, conditions are readily secured for the correct application of the method.

THE PHYSICAL SOCIETY OF LONDON.

A DISCUSSION

ON

HYGROMETRY.

Held on November 25, 1921,

AT THE

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY,
SOUTH KENSINGTON, S.W.7.

LONDON:
THE FLEETWAY PRESS, LTD.,
DANE STREET, HOLBORN, W.C.1.

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THE MEASUREMENT OF ATMOSPHERIC HUMIDITY.

BY

SIR NAPIER SHAW, *F.R.S.*

So far as meteorological practice is concerned, hygrometry, the measurement of water-vapour in the atmosphere, has to be approached from the point of view of the daily observer, and therefore any practical process must be capable of repetition daily, once, twice or thrice, year in and year out, without fail. The whole subject of hygrometry bristles with points of interest for the student of physics who has a laboratory at his disposal. Many of the questions involved may be, or become, of practical importance in the measurement of vapour ; but the practical determination of humidity must be of such a nature that for regular observations it can be entrusted to an attendant who has no experience of work in a laboratory, who can follow a prescribed routine. He has to make his observations alone, his records reported to and used by people who may never have seen him or the conditions under which he is working. If a particular reading seems unreasonable, it may be rejected, but it cannot be corrected. Any symptoms of unreasonableness that appear in a schedule of observations of humidity render the whole series unusable on account of general discredit.

Hence the mode of procedure must be to regard the observer as a tool-user, not as a tool-minder, still less as a tool-maker.

For that reason, meteorological practice in the measurement of humidity is limited to the wet and dry bulb thermometers, which are used almost everywhere, and the hair hygrometer, which is used for the term hour observations in Norway and for self-recording hygrometers everywhere.

There is little difficulty about the use of the wet and dry bulb so long as the temperature of both remains above the freezing point. The formula for reduction depends to some extent on wind velocity, and in dry climates, like that of Egypt, a small error in formula may lead to ridiculous results in practice ; if anything vital turned on the results, there is little doubt that a system would be evolved without difficulty. But as soon as the freezing point is passed the wet bulb ceases to be an effective instrument. The water has no definite freezing point, but freezes at all sorts of temperatures, and when the water is frozen the capillary action, upon which the moistening depends, ceases altogether. The directions for the treatment of the wet bulb during frost are palliatives designed to carry on in an occasional emergency. Nobody in London could possibly satisfy himself from the evidence at his disposal whether a reading of humidity during frost entered in a schedule from, say, Yarmouth, or on board a ship, represented frozen bulb, super-cooled wet bulb, semi-dry bulb or dry bulb. In these circumstances, equality of reading of wet bulb and dry bulb, the most probable occurrence in the circumstances, has no effective meaning.

In explanation of the vagaries of freezing wet bulbs, I refer to some experiments made for me by Sir James Dewar, and noted in the " Computer's Handbook," and for some general remarks on the uncertainty of freezing at the freezing point to some remarks by Dr. J. Aitken in a Paper on " Frazil-ice " in the Journal of the Scottish

Meteorological Society, Vol. XVIII. Moreover, below the freezing point the amount of water-vapour in the atmosphere and its variations become very small. There is very little to go upon when dealing with absolute measures. It is, however, remarkable that the shrinkage and slacking of cordage and other results upon animal and vegetable fibres are apparently as effective as at any other temperature.

The conclusion at which I have arrived is that the wet bulb is useless for temperatures just below freezing, and should be discarded. Descriptions of the endeavour to find a suitable formula abound in meteorological literature ; but practically the subject has not advanced at all in my time.

So far as I know, the hair hygrometer is the only instrument which is available in those circumstances to give a reading which can be interpreted. Since the publication of Regnault's classical memoir, physicists have been very shy of it, because it offends the first principles of a physical laboratory ; it does not always repeat the same reading in the same physical conditions. It suffers from age and misuse and other infirmities. But in view of the general failure of more orthodox methods, the prejudice of the Physical Laboratory against the instrument is a little overdone and unreasonable. I suppose that there is a limit beyond which even the most accurate physical experiment does not repeat itself—that is to say, unrecognised causes supervene. And in an atmosphere where rejoicing in the triumphant accuracy of one part in a hundred thousand is a common experience, it is annoying to be brought up by a matter that cannot keep steady within 5 per cent. Yet hair is apparently a more definite physical quantity than wet muslin.

Certain it is that the story which the recording hair-hygrometer tells of the variation of the humidity of the atmosphere at any temperature is an extremely romantic and interesting one ; and, even when its tabulated figures are erroneous, its sequences are valuable evidence of the course of events.

I have little personal experience of its working. I do not much like covering it with a damp cloth or wetting the hairs and calling the reading 95 per cent. ; and yet, considering that the atmosphere is always in turbulent motion, and a process of mixing is always going on, it is really doubtful whether the actual humidity of a small portion of the atmosphere is a physical quantity to be measured by any instrument freely exposed to the passing air.

Knowing what hair can do, we ought to find some substance which has corresponding structure and is less subject to change than a part of a living organism. Chemists may know of such substances. There is a transparent stuff called " cellophane," which is certainly hygroscopic, and may be more stable than hair ; but, if no such substance is available, then, it seems to me, some competent physicist ought to live for a while with two (or more) recording hair hygrometers, use one (or two) as a current recorder and experiment with the others, not for the purpose of showing that it may have serious errors, but to find out how they may best be reduced to manageable limits. We might then learn that, if the hairs are treated in a specified way, they will, or will not, recover their tone, that changing the hairs every week and treating them as prescribed, the reading will be accurate to within 5 per cent.

The uncertain physical condition of water in the region just below the normal freezing point is an obstacle to the introduction of many other devices for indicating the dew-point by a deposit of moisture. Perhaps the most definite hygroscopic indication is to be obtained from the same process which gave most conclusive evidence of the vagueness of the thermometric " fixed " points—namely, the formation of cloud. I suppose a sample of air in a thermos flask properly supplied with nuclei

nnot fail as an index of " below the dew-point " at any temperature ; the flask ight easily be boxed in so as to make an incipient cloud visible. It is not suitable r self-recording, but as an eye-method I think it must succeed.

The purpose of this note is to indicate that while investigations of various pects of humidity and condensation from the point of view of an accuracy of one-nth per cent. are always interesting, in the practical measurement of humidity below e normal freezing point a measure which could be relied upon within 5 per cent. ould be of some advantage, and could probably be realised with existing apparatus anyone who has access to air in varying conditions of moisture with a temperature low the freezing point. Such conditions occur in the open air of our observatories ; t so infrequently that continuous observations cannot be arranged. Artificial nditions on a large scale are required.

SOME MODIFIED FORMS OF HYGROMETERS.

BY

EZER GRIFFITHS, *D.Sc.* (*National Physical Laboratory*).

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7. THE HOT-WIRE TYPE HYGROMETER.

ABSTRACT.

The Paper describes experiments made with the object of developing suitable apparatus for the measurement of humidity at low temperatures. The three classical methods—the wet and dry bulb hygrometer, the dew-point apparatus, and the hair hygrometer—were studied and so modified that they could be used in a low temperature room inaccessible to the observer.

The common form of wet and dry bulb hygrometer is notoriously unreliable, but the ventilated form is quite satisfactory provided the wind velocity past the bulb exceeds

bout 3 meters per second. A tubular form of wet and dry bulb hygrometer was developed th an electric fan for aspiring the air past the bulbs. A continuously-recording, sistance thermometer, type was also made, which had a cam device for rapidly dipping id withdrawing the thermometer bulb at periodic intervals from a reservoir of water.

The dew-point apparatus was modified into a form suitable for permanent installation; the cooling of the polished metal surface being effected by pipe connections to the old brine circulation of the stores.

In another form a silver thimble, cooled by the evaporation of ether, was placed at ne end of a long aluminium tube and a telescope at the other. By suitable arrangements f mirrors and lamps both the silver surface and the thermometer column were thrown to the field of the telescope. The end containing the thimble was inserted into the nclosure through a circular aperture. The instrument was portable and self-contained.

A distant reading type of dew-point apparatus was constructed, in which the formation of dew was indicated by the change of reflecting power of the cooled surface. A eam of heat radiation was reflected from the polished surface and concentrated on to a inute thermopile. The thermo-junctions were connected to a pivoted indicator situated t the observation station where the observer controlled the flow of cooling fluid by means f a solenoid valve. The formation of dew resulted in a sharp falling-off of the reflecting ower and was indicated by the movement of the pointer of the instrument.

The hair hygrometer was studied under a variety of conditions and the changes n the calibration of this type of instrument, caused by exposure to low and high temperature, &c., were determined.

A very simple form of distant reading hair hygrometer was developed. In this the lockwork drum of the ordinary recorder was replaced by a tubular rheostat. The pointer was pressed into contact with the drum when a reading of the humidity was desired. The two portions of the resistance winding then constituted the two arms of a Wheatstone's bridge.

A number of other forms of hygrometers were also studied, notably the one utilising the heating effect on dry cotton when exposed to a humid atmosphere.

A convenient form of apparatus for the calibration of hygrometers over a wide range of humidities is described. It consists essentially of a drum fitted with a heavy glass front making an air-tight joint. The drum contains an electric fan which circulates the air over a dish of strong sulphuric acid. This method of reducing the humidity is more effective than bubbling and does not produce acid spray. The acid dish can be cut out of communication with the chamber by a ground glass cover operated by a lever projecting out of the drum.

Introduction.

Humidity and temperature are two variables which have a profound influence on the physical properties of materials of organic origin. One has only to study such industrial processes as the seasoning of timber, the drying of raw rubber, or the preservation of foodstuffs, to appreciate the necessity for control over both the humidity and the temperature of the surrounding atmosphere.

As regards the measurement of temperature, there are available at the present time a variety of reliable instruments which can be adapted to meet most requirements. Such a satisfactory state of affairs does not exist as regards the measurement of humidity. Yet the importance of a knowledge of the hygrometric state of the atmosphere appears to have been recognised from an early date. As far back as 1783 De Saussure devised the hair hygrometer, while Daniell invented the dew-point hygrometer in 1827.

The origin of the familiar wet-and-dry bulb hygrometer is not quite certain. It is stated that Sir John Leslie in 1813 converted his differential air thermometer

into a form of hygrometer by keeping one bulb wet and the other dry, and observing the temperature difference.

The simplicity of the wet-and-dry-bulb mercury hygrometer has led to the adoption of this instrument to the exclusion of practically all other types of hygrometers in meteorological and industrial work. The conservative attitude of scientific workers in this respect is greatly to be deplored, for it is now generally admitted that the instrument in its elementary form is very inaccurate.

It is a curious fact that no fundamentally new method of hygrometry has since been introduced, and the above instruments have remained the sole physical appliances available for routine tests. It is true that innumerable proposals have been made concerning novel hygrometric devices. Usually, however, such instruments are put forward without receiving adequate experimental investigation, and it often happens that humidity is but one of the many factors in operation.

The investigation described in the present Paper arose from an inquiry for suitable apparatus to use in measuring the humidity of the air in cold stores. It was considered that the design of the standard form of laboratory apparatus was unsuitable for this purpose, particularly when it was desired to measure the humidity without actually entering the room.

With the object of meeting these special requirements a study was first made of the three standard methods of hygrometry :—

(1) The ventilated wet and dry bulb hygrometer.
(2) The dew point apparatus.
(3) The hair hygrometer.

In the course of the work other methods of measuring humidity were also studied.

But before passing on to the description of the various appliances for the measurement of humidity it is necessary to consider the means available for adjusting to any desired value the humidity within a closed space. For it is essential in calibration work to be able to vary the humidity over a wide range without being dependent upon climatic conditions.

1. Apparatus for Obtaining Variable Humidity.

The problem of humidity control is not difficult if only comparatively small volumes of air have to be considered, but when it becomes necessary to vary the humidity in a space of, say, 10 cubic metres in capacity it becomes a troublesome matter, especially if an observer has to enter the room.

Since the experiments were primarily concerned with temperatures near 0°C., a sheet iron enclosure was constructed within a cold stores room. In this enclosure an electric fan was fitted to keep the air in rapid circulation. If a humidity value below normal was required the air was circulated over granulated calcium chloride. This salt was spread out on lead trays so inclined that the liquid drained off to reservoirs beneath.

With this arrangement it was possible to maintain a humidity as low as 45 per cent. with the observer in the room. The presence of the observer is a serious hindrance to the maintenance of a low humidity at a low temperature, for the quantity of water required to saturate a cubic metre of air at 0°C. is only 4·84 grams, and the average human being gives off 63 grams of water per hour when in repose

nd considerably more when exercising.* Hence it will be realised that very fficient methods of water vapour absorption must be employed if the humidity is o be maintained at a low value.

When it is practicable to carry out experiments in a closed vessel of moderate imensions, then the problem becomes decidedly simpler. For instance, with some ypes of hygrometers it is possible to make observations without the necessity of anipulating the instruments or aspirating considerable volumes of air out of the nclosure. Such is the case with the hair hygrometer, the dew-point apparatus,

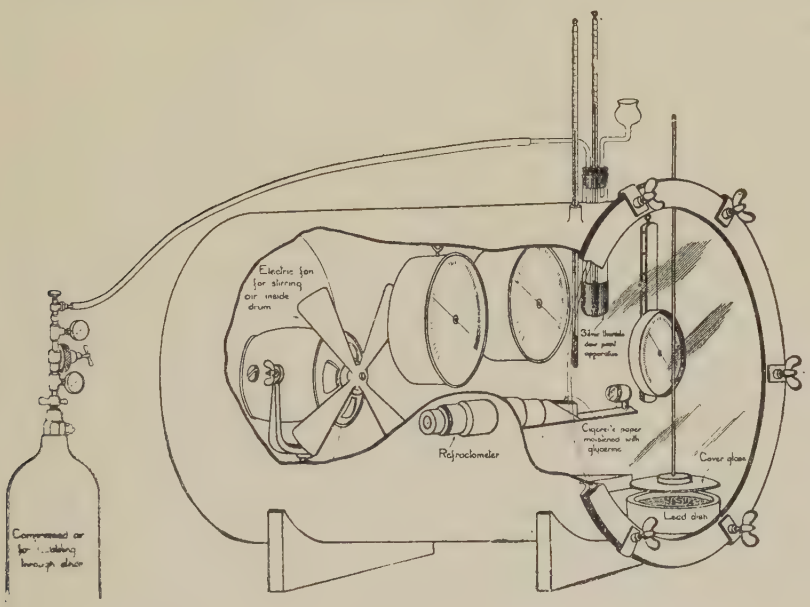

Fig. 1.

nd the refractive index of glycerine method. For some experiments the apparatus hown in Fig. 1 has been found to work admirably.

Description of Apparatus.

The apparatus consists of a sheet metal vessel 14 inches in diameter by 18 inches n length, closed by a piece of plate glass clamped down on a soft rubber packing so as to give an air-tight joint. A small electric fan is fixed in the drum which is switched on when it is desired to mix the air in the vessel before an observation. The humidity of the atmosphere inside the drum is varied by the aid of a lead dish containing strong sulphuric acid. The fan drives the air over the exposed acid surface and the humidity can be rapidly lowered. When the required point has been reached the dish is closed by a weighted glass cover carried from a rod. This is operated from without the enclosure. The humidity of the atmosphere can be

* About 1 gram per kilogram of adult human body per hour in repose. This quantity is extremely variable; the slightest exercise increases it enormously.—*Recueil de Constantes Physiques*, Société Française de Physique, p. 740.

raised by blowing in a little steam or merely by breathing into the drum through a piece of rubber tubing.

Driving the air by means of the fan over the exposed acid surface is a far more effective method of changing the humidity than by pumping the air round through wash bottles containing acid. This latter method was tried, and abandoned on account of its extreme slowness.

With the simple arrangement illustrated in Fig. 1 humidities down to 5 per cent. can be obtained with ease. To determine the actual value of the humidity a dew-point apparatus is installed as shown in the diagram. This consists of a silver thimble soldered on a piece of glass tubing. Air is bubbled through the ether and the temperature of the appearance and disappearance of the dew observed.

In our experiments this apparatus has worked satisfactorily over the range of temperatures from −8°C. to +40°C. When studying the behaviour of the instruments in atmospheres of very low humidities the dew-point was lowered as far as −28°C. (−20°F.), a depression of 21°C. below the air in the enclosure. Even with these extreme conditions the method was workable; and under the circumstances it would have been impossible to employ the chemical method.

In addition to the dew-point method a special form of Abbé refractometer was tried, so as to obtain the humidity on a direct reading scale. This instrument will be seen projecting in from the left-hand side. The prism and the telescope are rigidly fixed and the refractive index read from a scale in the eye-piece. The surface of the piece of cigarette paper, moistened in glycerine,* is illuminated by the small bull's-eye electric lamp.

The procedure in making the tests was to bring the air to the desired humidity approximately, close the sulphuric acid vessel (the top of the lead vessel and the plate had been ground to a good fit), and allow the fan to run for some time to mix up the contents of the drum thoroughly. After an interval the fan was stopped, the instrument read, and the dew-point observed.

Another method of obtaining air of a definite humidity is to bubble through H_2SO_4 solution of appropriate density. The advantage of this procedure is that it is not necessary to determine the humidity, but only to ensure that the moisture content of the air is that of the partial vapour pressure corresponding to the strength of sulphuric acid solution employed. The usual procedure is to bubble the air at the rate of 50 c.c. to 100 c.c. per minute through two or three wash bottles in series.

An essential precaution in the use of this method is to pass the air through a tube rather tightly packed with glass wool, so as to remove the particles of sulphuric acid carried over by the air stream.

This tendency of the acid spray to be carried over when bubbling air through the solution is troublesome to overcome. For example, in attempting to obtain air of definite humidity in a large cylindrical vessel by bubbling air through a layer of acid in the bottom, it was found that the air near the top of the vessel and at a distance of 18 in. away from the liquid surface was acid in reaction to litmus paper. This feature rendered the method impracticable for the experiments described in this Paper.

* A solution of glycerine will evaporate or condense water vapour from the surrounding atmosphere until the concentration of the solution is such that it is in equilibrium with the aqueous vapour pressure prevailing.—(Giraud).

For studying the humidity equilibria of various substances which can be packed into U-tubes of small capacity the above method appears to be quite satisfactory, and it might be observed that accurate control of the temperature is not very important, since the moisture content of most organic materials varies but little with moderate changes in temperature, providing the relative humidity is maintained constant.

TABLE I.—*Strength of* H_2SO_4 *Required to give Definite Humidities.*

Relative Humidity.	Per cent. Sulphuric Acid required at			
Per cent.	0°C.	25°C.	50°C.	75°C.
10	63·1	64·8	66·6	68·3
25	54·3	55·9	57·5	59·0
35	49·4	50·9	52·5	54·0
50	42·1	43·4	44·8	46·2
65	34 8	36·0	37·1	38·3
75	29 4	30·4	31·4	32·4
90	17·8	18·5	19·2	20·0

NOTE.—The values given in the above table were computed by R. E. Wilson from the experimental data of Regnault, Sorel, Helmholtz, Bronsted and Dieterici. *See* Journ. of Industrial and Engineering Chemistry, Vol. XIII., No. 4, p. 326 (1921).

Reference to Table I. shows that for a temperature change of about 10 deg. the relative vapour pressure of most of the solutions is practically constant ; it must not, however, be supposed that constant humidity conditions will be maintained in a closed space when subject to temperature change, unless the temperature of the entire apparatus is uniform throughout. Local irregularities of temperature produce very serious errors if diffusion is depended upon for equalising the humidity. Hence in precision work it may be assumed that thermostatic control over the temperature of the space is necessary.

An analogous method for use at higher temperatures is that employed in the Freas oven. This oven is designed with shelves on which suitable crystals containing water of crystallisation are placed. An air-circulating device is arranged so as to sweep air over these crystals, thus maintaining a humidity content corresponding to the dissociation vapour pressure of the water of crystallisation. An essential condition is that the chemical must be present in both the anhydrous and crystallised forms.

When the moisture content of the air becomes too great, owing to the material in the oven giving off a great deal of moisture, then the anhydrous salt will remove some of it, and be converted to the crystalline form. On the other hand, if the air is too dry the crystallised form will furnish the moisture required. Adjustment of the salt to the required state is effected by drawing unsaturated air over the chemical when the crystal form is in excess, and saturated air when the anhydrous form is in excess. It is stated that such treatment for an hour or so will prepare a mixture of the chemical in the proper proportion of crystal and anhydrous form for rendering it successful for maintaining constant humidity.

By this method it is possible to obtain a range of humidity up to temperatures as high as 80°C., but, of course, it is advisable to control the temperature by a thermostat arrangement.

In Table II. some figures are quoted from the catalogue of Messrs. Eimer & Amend to indicate the possibilities of the method.

TABLE II.—*Dissociation Tension with Loss of Water of Crystallisation.*

Temperature Degrees C.	Tension of Water.	Tension of Water Vapour.			
		$CuSO_4—5H_2O$	$MgSO_4—7H_2O$	$ZnSO_4—7H_2O$	$FeSO_4—7H_2O$
		mm.			
20	17·4	6·0	...	10·1	10·9
30	31·5	11·6	27·0	20·2	20·3
40	54·9	22·4	47·2	44·2	40·1
50	92·0	42·0	75·7	73·1	74·8
60	148·9	...	122·5	113·9	131·3
70	233·3	...	186·0	170·8	205·2
78	327·0	234·0	...	258·5	321·9

2. Standard of Reference in Calibration Work on Hygrometry.

In calibration work it is generally accepted that the chemical method is the ultimate standard of reference.

In our early experiments at low temperatures we found the chemical method exceedingly tedious to operate. There was also the fact that the absolute weight of water, for a given percentage of humidity, was considerably reduced at low temperatures ; and difficulties were encountered owing to dew deposition on the weighing tubes, &c. So, although it was possible with care to obtain a reasonable degree of accuracy by this method, we were soon forced to seek for more expeditious appliances for calibration work.

Of the three physical methods of hygrometry, the dew-point apparatus stands out conspicuously as being the one instrument which has a sound theoretical foundation and, further, it has the practical advantage that it is as easy to manipulate at low temperatures as at room temperatures. After a lengthy experience with the various methods under the most diverse conditions we have come to the conclusion that the dew-point is the most convenient of all methods for low temperature work ; and, consequently, it has been employed as standard of reference for most of the work recorded in this Paper.

3. Wet and Dry Bulb Hygrometer of the Ventilated Type.

Whilst the unventilated type of wet and dry bulb hygrometer is a notoriously unreliable instrument, it does not appear to be sufficiently well known that by so modifying the construction that air at a definite velocity is drawn past the thermometer bulbs, it can be converted into an instrument of satisfactory precision.

This important fact was demonstrated by the Italian physicist Belli in 1830, and in view of the simplicity of the device it is somewhat surprising that the stationary form of wet and dry bulb hygrometer is tolerated at all at the present day.

In the familiar equation* for the wet and dry bulb hygrometer,

$$p = p_w - AP(t - t_w)$$

* Attempts have been made by various scientists to deduce from theoretical considerations the relation between the vapour pressure of the aqueous vapour in the air and the difference of temperature between the dry and the wet bulbs. Not one of these is satisfactory, and the simplest plan is to use an empirical equation of the above form.

where t=air temperature.

t_w=wet bulb temperature.

p=pressure of aqueous vapour in the air.

p_w=saturation vapour pressure at the temperature of the wet bulb.

P=barometric pressure.

A=a quantity which for the same instrument and certain conditions is constant, or a function depending in a small measure on t_w.

The value of A differs materially according to whether the wet bulb is in quiet or in moving air; it is in this connection that the use of a forced air-stream past the bulb becomes of fundamental importance. In theory the value of A depends upon the size and shape of the thermometer bulb, size of stem, and velocity of the ventilation; so that different formulæ are required for different forms of instruments. But using an air velocity exceeding about three metres per second the differences in the results given by different instruments vanish, and the same tables can be adapted to any kind of thermometer, and to all changes of velocity above that which gives sensibly the greatest depression of the wet bulb temperature; and with this arrangement there is no necessity to measure or estimate the velocity in each case further than to be certain that it does not fall below the assigned limit.

It is not difficult to obtain sufficient velocity of the air past the bulbs, since all that is necessary is to fix the two thermometers securely on a rod and swirl them round. Espy at a very early date noted the advantage of this procedure, for he states: "When experimenting to ascertain the dew-point by means of a wet bulb, I always swung both thermometers moderately in the air, having first ascertained that a moderate movement produced the same depression as a rapid one."*

The most popular form of ventilated wet and dry bulb hygrometer is the Assmann type. In this the two thermometers are fixed alongside each other in two tubes, and a clockwork-driven fan sucks air past the bulbs. Before each series of observations the instrument requires winding up, and the muslin sack around the wet bulb thermometer needs moistening with distilled water.

Tables † are published covering the temperature range from −30°C. to +40°C., for converting the readings into relative humidity; the same operation can be performed graphically.

We have made a large number of observations with this form of hygrometer, and compared its indications with those of a dew point apparatus. At room temperature its readings agreed with those of the dew-point apparatus within 1 to 2 per cent., but at low temperatures the divergence was greater on account of the disturbance caused by the observer when reading the thermometers at close quarters. The actual data will be found in Columns 4 and 5 of Tables IX. and XIII.

The following observations may also be quoted as illustrating the degree of concordance obtained with three ventilated psychrometers obtained from various sources (Continental and British) when compared with a dew-point apparatus. In

* Smithsonian Meteorological Tables, 4th edition (1918).

† Aspirations—Psychrometer—Tafeln. Published by Vieweg Braunschweig.

each case, of course, corrections were applied to bring the mercury thermometer readings to true temperature.

TABLE III.—*Psychrometer Readings.*

Instrument No.	Wet bulb temperature.	Dry bulb temperature.	Relative humidity.
1	13·3°	17·3°	64 per cent.
	13·5°	17·8°	62 ,,
2	13·6°	17·2°	67 ,,
	13·8°	17·9°	64 ,,
3	13·6°	17·5°	65 ,,
	13·9°	18·1°	63 ,,

Dew-point Apparatus.

Air temperature.	Dew appears.	Dew disappears.	Mean reading.	Relative humidity.
17·2	10·15°	10·35°	10·25°	63·7 per cent.
17·8	10·55°	10·65°	10·6°	62·7 ,,

(*a*) *Determination of Velocity of Air Stream Past the Wet Bulb.*

It is always advisable to test an instrument to ensure that the velocity of the air stream past the bulb is of the order of 3 metres per second. This can be effected by connecting on to the tube surrounding the wet bulb a glass tube, and determining the speed of a puff of smoke along the glass tube. An alternative method is to measure the velocity in the extension tube by means of a Pitot tube and sensitive gauge, making corrections for the relative cross-sections of the extension tube and annular space around the bulb. Since only an approximate check is usually necessary, the smoke method is quite effective.

One practical defect of the Assmann design is the possibility of water being squirted over on to the dry bulb when saturating the sack around the wet bulb. This, of course, vitiates the readings.

(*b*) *Tubular Psychrometer.*

We constructed a modified form of instrument which permitted of observations being taken without the observer entering the room. In this arrangement an electric fan aspired the air past the bulbs contained in a steel tube 2·7 cm. in diameter and 70 cm. long. The complete instrument is shown in Fig. 2. The motor was directly connected to the 100-volt supply, and took 0·1 of an ampere. After once moistening the sack around the wet bulb, the instrument would continue to operate for 40 minutes without attention.

(*c*) *Experiments below* 0°C. *with the ordinary form of Assmann Psychrometer.*

At temperatures below 0°C. the water freezes on to the muslin bag, but the instrument still operates fairly satisfactorily.

In order to obtain the data necessary for the design of a distant-reading wet and dry bulb instrument, which would act automatically and could be placed at a considerable distance from the recording station, some observations were made with a standard mercury thermometer type of Assmann psychrometer. In these experi-

nents the instrument was set up in the cold stores room and observations taken at ntervals for a period of $3\frac{1}{2}$ hours, the observer entering the room occasionally to wind up the clockwork and read the thermometers. Reference to Fig. 3 will show he curves obtained.

Initially, both bulbs were dry, and at approximately the same temperature about—3·5°C.). The muslin around the wet bulb was moistened with water, whose tem- perature was above 0°C., and the fan started. The reading of the thermometer then

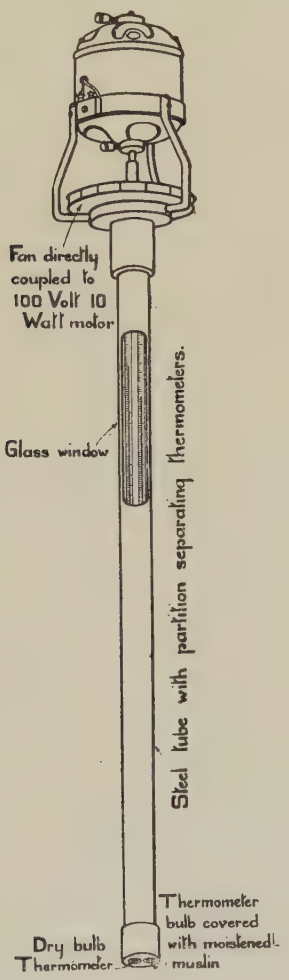
Fan directly coupled to 100 Volt 10 Watt motor
Glass window
Steel tube with partition separating thermometers.
Thermometer bulb covered with moistened muslin
Dry bulb Thermometer

FIG. 2.

dropped quite rapidly to —4·4° under the influence of the air current. It will be observed from an inspection of the data in Fig. 3 that the temperature fell to this value in $3\frac{1}{4}$ minutes. At this point, apparently, the under-cooled water froze and the temperature rose sharply to 0°C. Then the frozen mantle cooled down and acquired an equilibrium temperature about 1° below the dry bulb after an interval of 10 minutes from the time of the initial moistening. From this point forward for

a period of about two hours the difference between the two thermometers was practically constant. In Fig. 3 the time scale after the first 10 minutes is contracted up so as to include the respective temperatures over a long interval of time. The violent oscillations of temperature were due to the observer going in and out of the cold stores room and disturbing the thermometers when winding the clockwork at intervals of about ten minutes.

(d) Low Temperature Distant Reading Psychrometer.

From the results of the above experiment it appeared that saturating muslin in water at intervals of from 1 to 2 hours would suffice, so the problem resolved itself

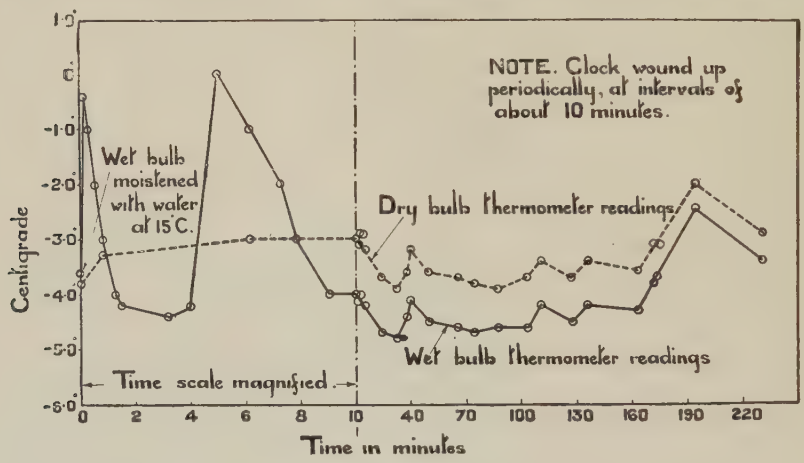

FIG. 3.

to devising a mechanical device by means of which the wet bulb could be periodically saturated with water. It was, of course, necessary to maintain the water into which the bulb was dipped at a temperature above 0°C. by the use of a small heating coil. It would have been easy to perform the dipping by a clockwork arrangement, but since an electric fan was required for producing an air stream past the bulbs, it was decided to utilise the same motor for operating the dipping mechanism.

The essential condition to be complied with was that, at the desired instant, the thermometer should be plunged into the water fairly rapidly, kept there for a period sufficient to ensure that any residual ice was melted, then withdrawn sharply and restored to its normal position in front of the fan. To effect this motion the arrangements shown in Figs. 4 and 5 were constructed. The resistance thermometer is carried from the end A of the arm AB. This arm prolongs to C, where it terminates in a small pin projecting out at right angles to the arm. Parallel to this extension BC is a spring S, with a pin projecting at its end. BC and S are situated in front of the face of a disc. This disc is rotated at the rate of one revolution per two hours by means of the reduction gearing from the motor. A square section ring projects out from the plane of the disc, which has two slots cut in it. In the ordinary way, the pin C rides on the inner or outer circumference of this projecting ring. On the face of the disc are two inclined planes O and P. In the course of the rotation the pin at the end of the spring comes into contact with the inclined plane O. It travels up the

plane, and the spring is thereby depressed towards the centre of the disc. The compression of the spring tends to rotate the arm *AB* and, consequently, when the pin *C* comes opposite the slot it slips through, and end *A* of the arm *AB* is raised. Referring to Fig. 4, the arm is shown in the position when the pin *C* has just slipped through the slot.

During the next period of rotation the pin *C* rides upon the inner circumference of the ring and the thermometer remains stationary in the air breeze. When the

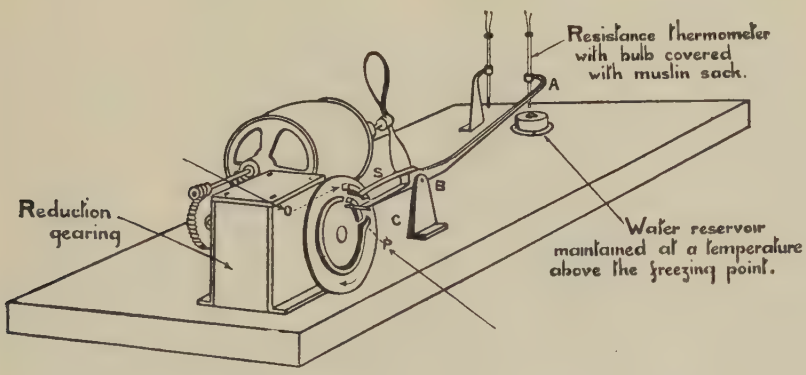

FIG. 4.

disc has nearly made a complete revolution, the pin projecting from the spring *S* comes into contact with the inclined plane *P*, set at such an angle as to pull away from the centre of the disc. Consequently, when the pin *C* reaches the slot, it passes through from the inner to the outer circumference of the projecting ring. In so doing the point *A* is depressed, and the thermometer bulb plunges into the water.

For the comparatively short period that the pin *C* is travelling on the outside

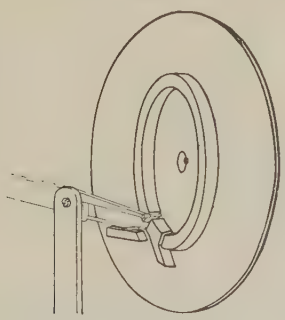

FIG. 5.

circumference of the projecting ring the bulb remains immersed in the water. As the rotation of the disc continues, the pin at the end of the spring travels up the inclined plane *O*, and the compression of the spring forces the pin *C* through when it arrives opposite the slot, thus withdrawing the thermometer from the water.

In Fig. 5 the same management is shown in a slightly modified form. Here the pin *C* rides on the outer circumference of the ring when the thermometer is in the "up" position.

The rest of the apparatus needs no detailed description. The resistance thermometers were constructed with very small compact bulbs, as the amplitude of the motion was limited. The condensation of moisture within the sheaths on the thermometer coils had to be guarded against by careful sealing. In our experiments the wet and dry bulbs were connected up differentially to a thread recorder.

A distant reading hygrometer of this character does not involve much more

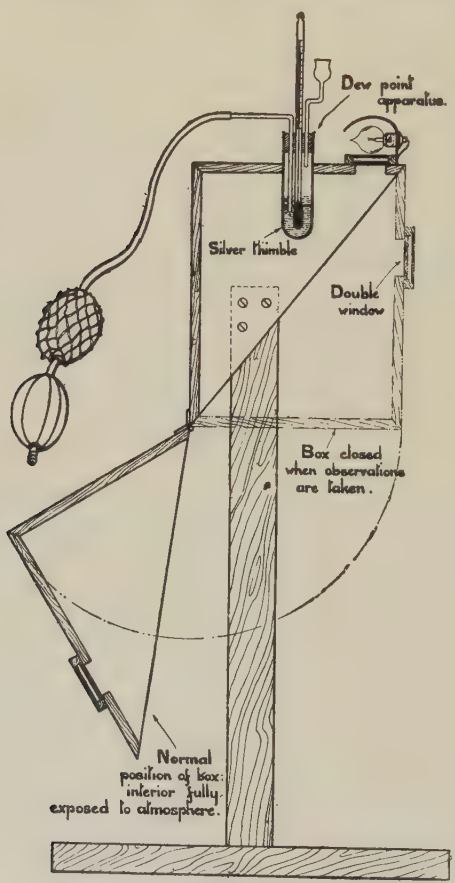
Dew point apparatus.
Silver thimble
Double window
Box closed when observations are taken.
Normal position of box: interior fully exposed to atmosphere.

FIG. 6.

apparatus than is necessary for the recording of temperature by the use of a resistance thermometer outfit, since the expensive items of both equipments are identical.

4. The Dew-point Hygrometer.

Although numerous attempts have been made to formulate some consistent theory for the wet-and-dry-bulb hygrometer, the nature of the assumptions which have to be made are such that the resulting formulæ will not stand experimental test. The dew-point method, on the other hand, is based on straightforward physical facts and the theory is so simple that it inspires confidence in the results obtained with the instrument.

For our requirements it was necessary to be able to operate the hygrometer n a somewhat confined space, and we developed, after a few preliminary experiments, the form shown in Fig. 6. The polished-silver thimble contains the hermometer and tubes for bubbling air through the ether. This is situated in he lead-lined box cut diagonally as shown. By oscillating the lower half of the box

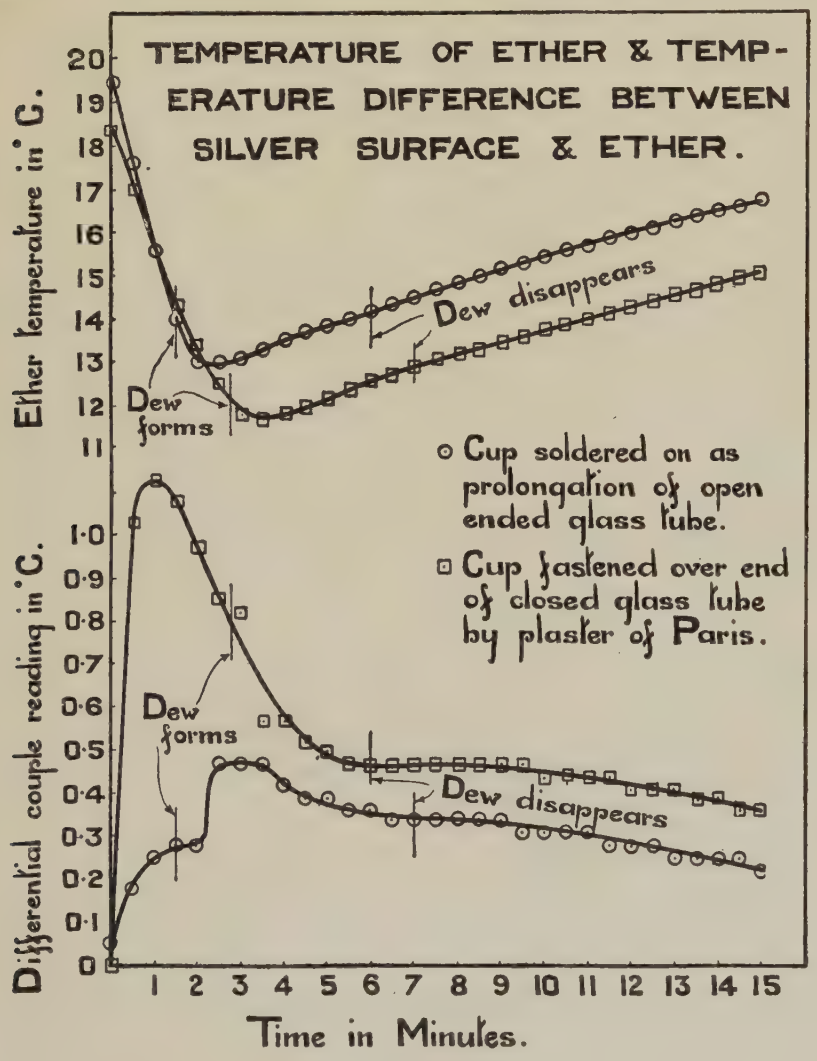
TEMPERATURE OF ETHER & TEMPERATURE DIFFERENCE BETWEEN SILVER SURFACE & ETHER.
Ether temperature in °C.
Differential couple reading in °C.
Dew forms
Dew disappears
Dew forms
Dew disappears
Cup soldered on as prolongation of open ended glass tube.
Cup fastened over end of closed glass tube by plaster of Paris.
Time in Minutes.

FIG. 7.

t is possible to ensure that an average sample of air is obtained. The box is then closed and the observer sets the air bubbling and watches the formation of the dew through the double windows in front. The use of a box around a dew-point apparatus has the great advantage that it practically eliminates the disturbing influence of the observer in the vicinity of the apparatus, and this is a most important

factor in low-temperature work, for it will be remembered that less than 5 grams of water will saturate a cubic metre of dry air at 0°C.

The box method has the additional advantage that it eliminates the disturbances of convection currents and draughts in the room.

(*a*) *Temperature Difference between Thermometer and Silver Surface.*

A point of importance in connection with the method is the measurement of the difference in temperature between the thermometer in the ether and that of the external surface of the thimble on which the dew is deposited.

To ascertain the magnitude of this a differential couple was made up of copper constantan. One junction was soldered to the surface of the silver thimble and the other attached to the bulb of the thermometer. The difference of temperature between the two junctions was observed at successive time intervals by means of a potentiometer.

Two forms of apparatus were tested; in the one the silver cup was soldered on as a prolongation of a glass tube, whilst in the other the cup was cemented on to a closed glass tube by means of plaster of Paris. This second method of fixing is, of course, not to be recommended, but we have found it employed in apparatus sold for teaching purposes. The glass and plaster are poor heat conductors and often the defect is aggravated by the plaster not being a continuous layer but full of air bubbles.

The results obtained in the two experiments are shown graphically in Fig. 7. The upper curves refer to the temperature of the ether during the period of cooling and warming up, while the lower curves are the readings of the differential couples. It will be observed that in the case of the thimble attached by plaster of Paris the surface of the silver is 0·8°C. warmer than the ether when dew forms and about 0·4°C. when it disappears. The soldered thimble, on the other hand, is only 0·28°C. warmer when dew appears and 0·35°C. when it disappears.

We found it advisable in practice to bubble air through the ether at intervals in the period when dew had formed and the temperature was slowly rising until it disappeared. By a little practice it was possible to mix the ether without causing appreciable evaporation.

(*b*) *Estimate of Weight and Thickness of Dew Deposit.*

Another question of considerable interest in connection with the dew-point method is the estimation of the weight of deposit required to give a visible indication of its presence on the surface.

Such estimates were arrived at by several independent methods and observers.*

(1) *By Weighing a Film.*

(*a*) A silver thimble of 17·4 sq. cm. area was weighed, cooled down, exposed to the atmosphere of the room until a deposit appeared, sealed in a weighing-jar and again weighed.

* I am indebted to my colleague, Mr. A. H. Davis, for most of the observations on weight of dew deposition.

The following results were obtained in a series of experiments :—

TABLE IV.

Experiment.	Weight of Deposit.
1	0·0016
2	0·0013
3	0·0011
4	0·0009
5	0·0008
6	0·0012
	Mean 0·0011

Hence the weight of deposit per square centimetre $=6{\cdot}3\times10^{-5}$ gms.

Results of the same order were obtained by another method. In this a film was deposited directly on the balance pan by breathing on it. The change of the equilibrium position of the pointer of the balance was observed by the usual method of oscillations. The pointer deflection scale was calibrated by noting the effect of changes in position of the rider. It was found that with no film the calculated zero would be in a certain position. A film altered the zero and, as the film gradually disappeared, the pointer gradually returned to its old zero. As the day was a wet one the rate of evaporation was not unduly great, being about 0·5 milligram per complete oscillation.

About four-fifths of the balance-pan area was covered with deposit equivalent to an area of 55 sq. cm.

The following results were obtained :—

TABLE V.

Experiment.	Weight of Deposit.
1	0·005 gms.
2	0·006
3 Extra heavy film.	0·008
4 Slight film.	0·002

Thus the mass of water deposit per square centimetre lies between $3{\cdot}6\times10^{-5}$ gms. and 14×10^{-5} gms. for slight and thick deposits respectively.

(2) *By Interference Colours.*

A film was obtained by breathing on a piece of platinised glass. With relatively thick films rather impure colours were visible, such as reddish brown.

Assuming these to be due to the usual interference effects with thin films, it appears that the thickness in this case is of the order of three or four wavelengths of light.

So the mass of water per square centimetre of surface would be about

$$24\times10^{-5} \text{ gms.}$$

(3) *From Water Vapour in one Breath.*

In normal breathing a person takes 16 breaths per minute, or $2{\cdot}3\times10^{4}$ per day.

The total weight of water breathed out per day on the average is about 10 oz. = 300 gms. Hence the weight of water in one *normal* respiration is

$$\frac{300}{2{\cdot}3\times10^{4}}=1{\cdot}3\times10^{-2}\text{ gms.}$$

One ordinary breath will dew over an area of 100 sq. cms. Hence assuming all the water in the breath is deposited the weight per square centimetre becomes

$$13\times10^{-5}\text{ gms.}$$

An alternative method of obtaining a similar estimate is to consider a *full* breath.

A full breath includes

Tidal air	30 cubic in.
Complementary air	100 ,, ,,
Supplementary air...	100 ,, ,,
Total	230 ,, ,,

This total together with the 100 cubic in. of residual air which always remains in the lungs makes up the total lung capacity of 330 cubic in.

In a normal respiration a person breathes out 30 cubic in. which as shown above contains $1{\cdot}3\times10^{-2}$ gm. of water.

Assuming a *full* breath to contain a correspondingly larger weight of water, we have for the weight in a full breath

$$1{\cdot}3\times10^{-2}\times\frac{230}{30}=0{\cdot}1\text{ gm.}$$

The area dewed over by a full breath is roughly 1,000 sq. cm. Hence, if all water vapour is deposited the thickness of the film is 10^{-4}, and the mass of water vapour per square centimetre is 10×10^{-5} gm.

Now 1 c.c. of air saturated with water vapour at 20°C. contains $1{\cdot}7\times10^{-5}$ gm., and at 0°C. $0{\cdot}48\times10^{-5}$ gm. So that we can calculate from the above estimates the volume of dry air that the weight of water in the film would saturate.

TABLE VI.

Method.	Magnitude of dew film expressed as :—		
	Gms per sq. cm.	C.c.s of dry air that dew on 1 sq. cm. of the surface would saturate.	
		At 20°C.	At 0°C.
Weighing :—			
(*a*) Normal film	$6{\cdot}3\times10^{-5}$	4	13
(*b*) Slight film	$3{\cdot}6$	2	7
(*c*) Heavy film.....	14	8	29
Interference colours ...	24×10^{-5}	14	50
Respiration :—			
(*a*) Full breath.....	10×10^{-5}	6	21
(*b*) Ordinary breath	13×10^{-5}	7	27

(*c*) *Industrial Forms of Dew-Point Apparatus.*

(*i*) *Wall Fixture Type.*

The apparatus shown in Fig. 6 is hardly suitable for routine use in cold stores, b for this purpose we developed the form illustrated in Fig. 8. Here the silver himble is replaced by a nickel-plated block of copper which can be cooled by the rine circulation used for cooling the stores. The temperature of the copper is determined by means of a thermometer with its bulb fixed as close as possible to the lurface of the copper. The manipulation of this instrument is very simple. When n observation has to be taken the observer closes the glass front of the instrument

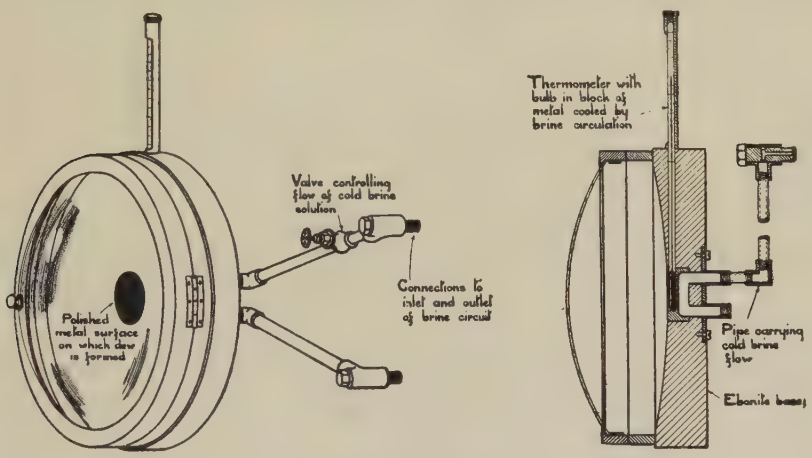
Thermometer with bulb in block of metal cooled by brine circulation
Valve controlling flow of cold brine solution
Connections to inlet and outlet of brine circuit
Polished metal surface on which dew is formed
Pipe carrying cold brine flow
Ebonite base

FIG. 8.

and turns on the brine supply. The temperature at the instant of dewing over is observed and also of the disappearance.

It may be of interest to quote some of the results obtained with this instrument.

TABLE VII.—*Test of "Wall Fixture" Type Dew-Point Apparatus.*

Experiment No.	Psychrometer readings.		Humidity.	Dew-point apparatus.		Humidity.
	Dry bulb thermometer.	Wet bulb thermometer.		Dew forms.	Dew disappears.	
			Per cent.			Per cent.
1	15·7	12·9	73	9·5	11·7	72
2	15·9	13·0	72	10·5	11·5	72
3	16·0	13·2	73	11·0	11·3	73
4	16·0	13·2	73	10·9	11·2	72·6
5	14·1	12·1	79	9·7	11·9	80
6	14·7	13·2	85	12·2	12·3	85

(*ii*) *Portable Form.*

It was found desirable to have an instrument which could be taken from place to place and inserted through the circular aperture built in the walls to permit of the insertion of the thermometers. For this purpose the hygrometer shown in Fig. 9 was constructed.

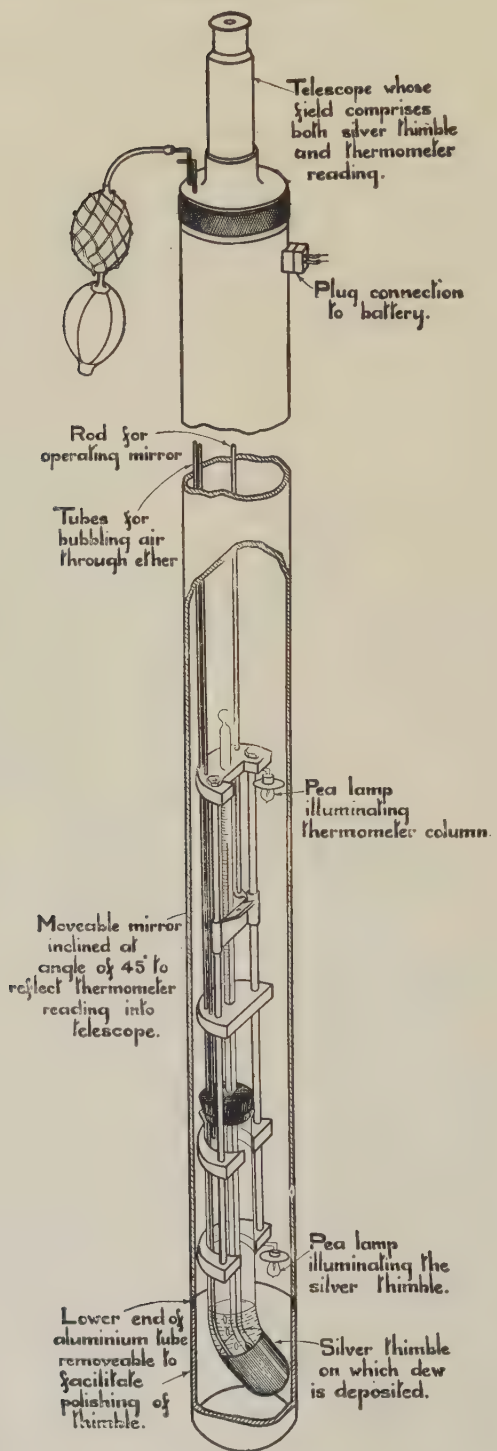
Telescope whose field comprises both silver thimble and thermometer reading.
Plug connection to battery.
Rod for operating mirror
Tubes for bubbling air through ether
Pea lamp illuminating thermometer column.
Moveable mirror inclined at angle of 45° to reflect thermometer reading into telescope.
Pea lamp illuminating the silver thimble.
Lower end of aluminium tube removeable to facilitate polishing of thimble.
Silver thimble on which dew is deposited.

FIG. 9.

It consists of an aluminium tube 8 feet in length by $2\frac{1}{2}$ inches in diameter. At one end of the tube the dew-point thimble is placed while a telescope is fixed to the other end.

The silver surface is an angle of about 45° to the axis of the tube, so that it is possible to view it directly from the telescope. This arrangement of the silver thimble has the additional advantage of permitting the apparatus to be operated with the axis of the tube either vertical or inclined with the thimble pointing downwards. The thermometer scale is read by the aid of a small mirror moving along guides, so as to maintain the meniscus of the mercury column in the field of view. Both the mercury column and the silver surface are illuminated by minute "pea" lamps set out of the field of view; a mirror being fixed opposite the silver surface to throw the light on to it.

In the vicinity of the dew-point surface a wide slot is cut in the aluminium sheath to permit of free access of air to the silver surface.

(*iii*) *Distant Reading Dew-point Apparatus.*

It will be observed that the dew-point method depends primarily upon the acuteness of vision of the observer to detect the formation of a trace of dew, and whilst it is possible, by the aid of a telescope, to operate the apparatus at distances up to 10 feet, for considerably greater distances it becomes necessary to find some other method of dew detection.

Now the dew-point method is essentially a discontinuous one and a prescribed cycle of operations has to be gone through for each determination of humidity. If these operations could be performed mechanically, without human intervention at any stage, we should have an industrial form of hygrometer possessing a sound theoretical basis.

It was anticipated that the conversion of the dew-point apparatus into a distant reading form would present unique practical difficulties and our anticipations were fully realised when the attempt was made to produce a continuously recording hygrometer working on this principle.

Some preliminary experiments indicated that a promising line to follow in the design of such an instrument would be to utilise the change of reflecting power of a metallic surface on the formation of dew.

The apparatus illustrated in Fig. 10 shows how this idea was applied in the construction of a distant-reading hygrometer.

The source of radiant energy is a gas-filled tungsten lamp. The energy is reflected from the plane surface on to the concave mirror* and thus concentrated on two minute thermo-junctions connected in series.

The indicator is located at a point convenient for observation and the instrument is worked in a similar manner to the standard form of apparatus; the only difference is that the observer watches the movement of the pointer instead of the surface on which dew forms.

The valve controlling the brine flow is operated by means of a solenoid. Until the dew formation the deflection of the pointer is steady, but simultaneously with the deposition of dew the reflecting power is diminished and the pointer moves rapidly toward zero. The temperature of the surface on which dew forms is then read by means of a thermo-junction.

* We are indebted to Mr R. S. Whipple for presenting us with the concave metallic mirror and thermo-junctions which are standard parts of Fery pyrometers.

This apparatus functioned satisfactorily and was tested against a psychrometer with the results shown in Table VIII.

TABLE VIII.—*Test on Distant Reading Dew Point Apparatus.*
(Typical Experiment.)

Time.	Deflexion of radiant heat indicator.	Temp. of metallic surface in °C.	Remarks.
Min. Sec.			
0	45·5	14·0	
30	45·7	14·1	
1 0	45·8	14·2	
30	45·7	14·0	
2 0	45·5	11·1	
30	45·0	9·1	
3 0	45·0	7·5	
30	45·0	6·5 ←	Dew forming.
45	41·5	....	
4 0	40·5	6·2	
30	39·0	6·5	
5 0	39·5	6·8	
30	44·5	7·1 ←	Dew disappearing
6 0	45·0	7·5	
30	45·3	7·7	

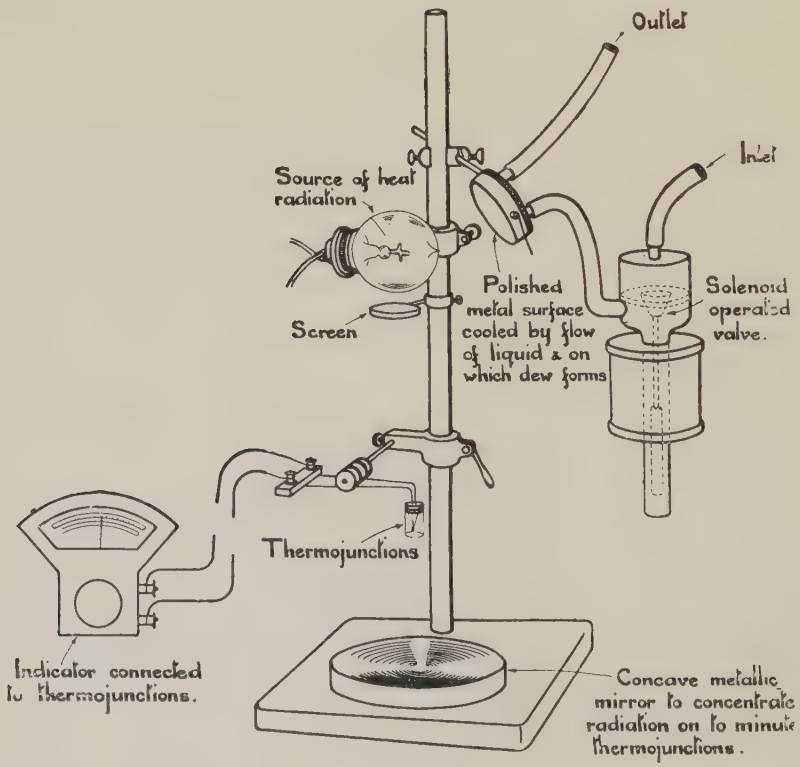
Outlet
Inlet
Source of heat radiation
Polished metal surface cooled by flow of liquid & on which dew forms
Solenoid operated valve.
Screen
Thermojunctions
Indicator connected to thermojunctions.
Concave metallic mirror to concentrate radiation on to minute thermojunctions.

FIG. 10.

If it were possible to work the indicator as a relay for operating the solenoid valve, then it might be possible to maintain the surface always at the dew-point temperature and thus obtain a continuous record of the dew-point in the room.

Hence taking the mean of the temperatures of appearance and disappearance the value found for the humidity is 59·5 per cent.

Taking the temperature of appearance only the value becomes 58·3 per cent.

Assmann psychrometer readings during the above series :—

Dry bulb temperatures = 14·6°, 14·7°.
Wet „ „ = 10·2°, 10·4°.

Hence humidity by psychrometer = 58 *per cent.*

Experiments have also been made on another method of indicating the occurrence of the dew point—namely, the change of electrical resistance of a surface on

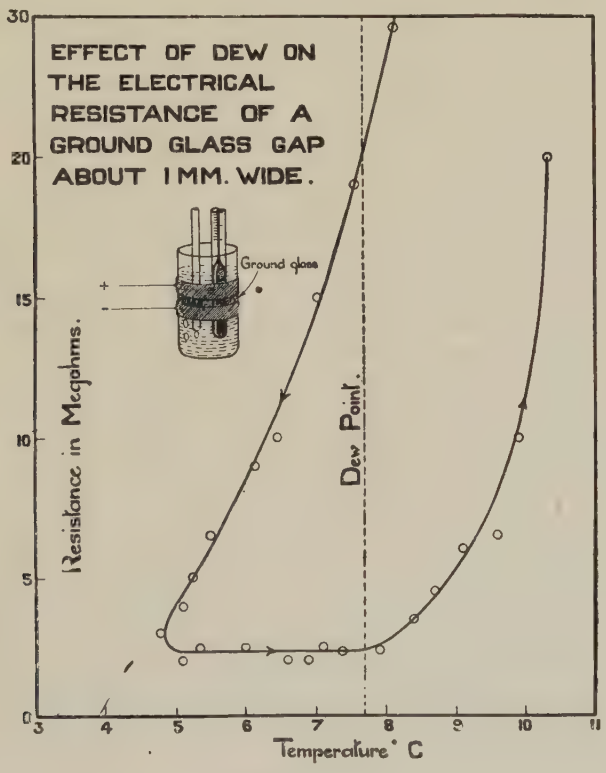

FIG. 11.

the deposition of dew. The apparatus used consisted of a test tube, on the outside of which were deposited two rings of platinum film with a small gap of one or two millimetres between them. The platinum films were connected to a "megger" or to the secondary of an induction coil with a telephone in series. The test tube was cooled down in the usual way by bubbling air through ether.

When the glass between the films was quite clean the resistance of the gap remained at infinity after the deposition of the dew. With the glass dipped in a solution of an efflorescent salt like sodium carbonate and dried out the resistance even when dry was too low. Finally, the method was adopted of grinding the glass before deposition of the platinum films. In this case breathing on the surface gave a very rapid fall and rise in resistance as the moisture was deposited and evaporated. When, however, the test tube was slowly cooled down to the dew point, apparently no very sharp change of resistance occurred, and consequently it was difficult to detect the point at which the dew appeared. One set of observations are shown in Fig. 11.*

The true dew point obtained by independent methods was at a temperature of 7·7°C. The tube was cooled down to 4·8C. and then allowed to heat up. It will be noticed that the resistance temperature curve did not return on itself, but that the resistance remained practically constant till the temperature rose to 7·9°C. (just above the dew point), when a rise of resistance occurred which became increasingly rapid. In another experiment where the tube was cooled *just* below the dew point, the curves of rising and falling temperature were much closer.

The reason for the effect obtained with a ground glass surface is not clear; possibly slight chemical decomposition is produced giving traces of soluble salts.

5. The Hair Hygrometer.

The two types of hygrometers already described require a certain amount of manipulation and computation before the value of the humidity can be ascertained.

This may not be of much consequence in laboratory work, but for every-day use a direct reading instrument of simple construction is much to be desired. A hygrometer possessing these characteristics is tolerable even if the accuracy of its indications is somewhat below that demanded in a laboratory instrument.

The hair hygrometer comes within this category. Besides the fact that it is direct reading, it has the additional advantage that it can be used at low temperatures, and so is applicable to cold storage work.

It utilises the principle that most substances consisting of organic tissue are hygroscopic, and change their length when they absorb or part with moisture.

Hair, free from grease, increases its length when moistened, and De Saussure's hygrometer works on this principle.

His original instrument has been greatly modified in mechanical detail since its invention, and modern forms of the instrument are illustrated in Figs. 12 and 13.

The hair hygrometer seems to have lost its reputation as a reliable instrument, but the evidence as to its unreliability is very meagre, and, so far as we have been able to ascertain, no serious scientific study of it has been made since the time of Regnault, three-quarters of a century ago.

For the purpose of this inquiry, five instruments were studied :—

One was of the form illustrated in Fig. 12, and will be referred to as type A.

Two were of the form shown in Fig. 13, which will be referred to as type B.

One was a recording hair hygrometer, while the other was an instrument which we had arranged for distant reading work (*see* Fig. 16).

* These observations were taken by Mr. F. H. Schofield, to whom our thanks are due.

It seemed desirable to have quantitative information on the following points, and experiments were made with this object in view :—

(1) The reliability of the instruments over a long interval of time when subject to moderate ranges of temperature and humidity (humidities from 45 per cent. to 95 per cent.).

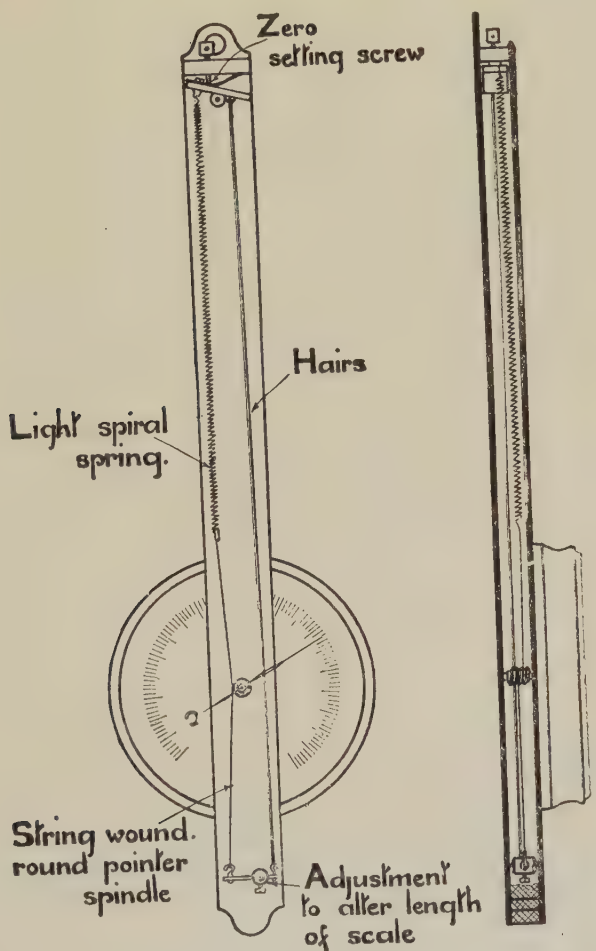

FIG. 12.

(2) The behaviour of the instrument when taken through a complete cycle of humidity changes such as from 7 per cent. to 90 per cent.

(3) The influence of temperatures below freezing point of water on the calibration curves.

(4) The effect of temperature changes above that of the room (for a nearly constant relative humidity of the atmosphere).

(a) Reliability over Long Intervals of Time.

Systematic observations were made over a period of three months at room temperatures (17°C.) and at temperatures about 0°C.

A range of humidity from 45 per cent. to 95 per cent. was covered, and it was considered that this was sufficient for the range of climatic changes met with in this country.

The dew-point apparatus was supplemented by the use of an Assmann psychrometer as standard of reference for obtaining the true humidity. A comparison of the data given in columns IV. and V. of Table IX. shows the close agreement between the results obtained with these two instruments, although fundamentally different in principle. The agreement is within 2 per cent. for practically all the observations taken at room temperature. The divergence at low temperatures is greater, and is probably due to the fact that the presence of the observer near the psychrometer disturbed the humidity conditions, whereas the dew-point apparatus was shielded by its box.

In the reduction of the observations on the hair hygrometers mean calibration curves have been drawn, and the divergencies of the individual readings from these curves are given.

A study of the data shows that when the instruments have settled down the divergencies are of the order of 4 per cent., with an occasional departure amounting

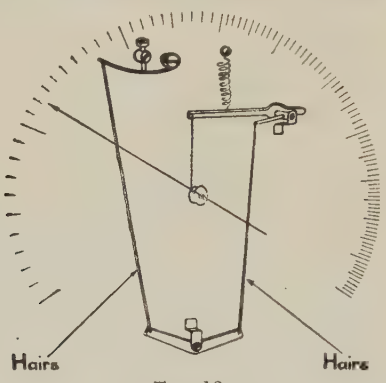

FIG. 13.

to 10 per cent. The bigger divergencies are possibly due to the lag of the instrument in getting to equilibrium value after a rapid change of humidity, and they generally occurred in all three simultaneously.

At low temperatures it was observed that the hair type of instrument was slow in settling to its final reading, particularly when it was taken from room temperature (15°C.) down to 0°C. For instance, when the instruments were taken into the cold stores it required $2\frac{1}{2}$ hours for the readings to settle to their equilibrium values.

It is, however, somewhat surprising that the calibration at room temperatures holds so satisfactorily at lower temperatures, for the absolute weight of water vapour per unit volume of the atmosphere for a given humidity varies considerably. For example, 85 per cent. humidity at +15°C. corresponds to 11 milligrammes of water per litre, whilst at 0°C. it corresponds to only 4 milligrammes of water per litre.

It would appear that hair behaves somewhat similarly to flannel, for which the moisture absorption depends on the relative humidity only, and varies but little with temperature.

TABLE IX.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
						Correction to mean calibration curve.			
Date.	Time.	Room temperature.	Humidity by psychrometer.	Humidity by Dew-point apparatus.	Mean value of humidity.	Hair hygrometer Type A.	Hair hygrometer. Type B.		Recording hair hygrometer.
							No. 1.	No. 2.	
Feb. 5	12 p.m.	14°	55	55	55	0	...	...	−3
,, 7	4 ,,	13°	52	53	53	0	...	...	−2
,, 16	1 ,,	15°	62	62	62	+9	...	...	+1
,, 17	1 ,,	16°	65	...	95	+11	...	...	+4
,, 18	...	17°	95	95	95	+11	...	...	+7
,, 19	10 a.m.	10°	73	74	74	+6	...	...	+5
,, 21	4 p.m.	15°	62	62	62	+6	...	...	+2
,, 22	11 a.m.	11°	69	69	69	+4	...	...	0
,, 22	3 p.m.	15°	63	62	63	+6	+5	...	+3
,, 24	3 p.m.	15°	66	68	67	+2	+2	...	...
,, 26	11 ,,	9°	63	64	64	0	0	...	+3
,, 28	5 ,,	9°	56	57	57	0	0	...	+1
Mar. 2	12 ,,	6°	52	50	51	−2	0	...	0
,, 3	12 ,,	6°	49	47	48	−1	−2	...	−1
,, 3	5 p.m.	7°	49	48	48	−1	−2	...	−1
,, 4	12 ,,	12°	46	46	46	0	−1	...	−1
,, 4	5 ,,	13°	46	46	46	0	−1	...	0
,, 5	12 ,,	14°	45	44	44	+2	+1	...	0
,, 7	12 ,,	12°	45	45	45	+1	0	...	0
,, 7	5 p.m.	13°	44	44	44	+1	0	...	0
,, 8	12 ,,	9°	46	44	45	0	−1	...	0
,, 8	5 ,,	7°	47	47	47	+1	−1	...	0
,, 9	5 ,,	4°	52	51	51	+2	+2	...	+1
,, 10	12 ,,	5°	47	47	47	+1	0	...	0
,, 10	5 p.m.	4°	48	47	47	+1	0	...	−5
,, 11	12 ,,	4°	52	51	51	−3	−4	...	−5
,, 11	5 ,,	0°	55	52	53	−4	−5	...	−7
,, 12	12 ,,	0°	54	51	52	−7	−8	−4	−10
,, 12	4 p.m.	0°	89	89	89	0	−2	−2	−2
,, 14	12 ,,	10°	83	84	83	+2	+2	+1	+2
,, 14	12 ,,	12°	79	79	79	+2	+2	+2	0
,, 15	12 ,,	12°	72	72	72	+2	+1	+1	+1
,, 15	5 ,,	13°	73	73	73	+3	+1	+2	+1
,, 16	12 p.m.	12°	72	74	73	+3	+1	+2	+1
,, 16	5 ,,	14°	71	71	71	+3	+1	+1	0
,, 17	12 ,,	12°	71	71	71	+2	+1	+1	0
,, 17	5 ,,	14°	84	84	84	0	0	0	−1
,, 18	12 ,,	14°	79	80	79	−1	0	+1	0

(*Continued on page* xxxiv.)

TABLE IX.—*Continued.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
						Correction to mean calibration curve			
Date.	Time.	Room temperature.	Humidity by psychrometer.	Humidity by Dew-point apparatus.	Mean value of humidity.	Hair hygrometer Type A.	Hair hygrometer. Type B.		Recording hair hygrometer.
							No. 1.	No. 2.	
Mar. 18	5 p.m.	15°	88	87	87	+1	+1	+1	—1
,, 19	12 ,,	15°	87	87	87	+3	+3	+33	+3
,, 21	5 ,,	15°	80	80	80	+1	0	0	0
,, 22	12 ,,	16°	82	80	81	0	—1	0	—1
,, 22	5 ,,	15°	68	67	67	+1	—1	+2	0
,, 31	5 p.m.	—1°	63	61	62	—5	—6	—3	—7
Apr. 1	12 ,,	.0°	78	75	76	—3	—5	—4	—7
,, 1	5 ,,	0°	92	90	91	0	—1	0	—3
,, 2	11 a.m.	—1°	87	82	84	—4	—6	—4	—7
,, 2	12 p.m.	—2°	72	69	70	—3	—2	—1	—3
,, 11	12 p.m.	15°	71	68	69	—2	—3	—2	—2
,, 14	5 ,,	14°	66	...	66	—1	—4	—2	—2
,, 20	5 ,,	12°	62	60	61	—1	—4	—2	—3
,, 21	12 ,,	12°	63	62	62	—2	—4	—2	—3
,, 21	5 ,,	14°	60	57	58	—2	—5	—3	—4
,, 22	5 ,,	15°	67	66	66	0	—3	—1	—3

A study of the table brings out the interesting fact that the hair hygrometer tends to read higher as time goes on, as is evidenced by the negative sign to the corrections during the latter period of the comparisons. Hence the hair appears to take up a permanent stretch.

In these experiments there were three variables : time, temperature and humidity. The main object of the experiments was to determine the magnitude of the changes to be anticipated for such fluctuations in these variables as would be encountered in practice, leaving for separate experiment the determination of the effect of temperature alone, etc.

It is interesting, however, to note that the results summarised in Table IX. clearly indicate that at lower temperatures the instruments read high, and this is in agreement with subsequent observations when temperature and humidity were the only variables.

(*b*) *Behaviour of the Instrument when Taken through a Complete Cycle of Humidities.*

For this part of the inquiry a more expeditious method than that adopted by Glaisher had to be found. In his comparison of the dry and wet bulb hygrometer with Daniell's hygrometer he obtained his high temperature points in India, his low and medium temperatures in Toronto, and the remaining odd thousand or so observations at Greenwich during the period 1841 to 1854.

The apparatus illustrated in Fig. 1 was employed for this part of the investigation, and by means of it a wide range of humidity could be covered in a comparatively short interval of time.

TABLE X.

Experiment No.	Date.	Time.	Room temperature.	Humidity by dew-point apparatus.	Correction to mean calibration curve.		
					Hair hygrometer Type A.	Hair hygrometer Type B.	
						No. 1.	No. 2.
1	May 7th	12.45 p.m.	16°	21	— 5	—10	— 9
2	,, 7th	3.0 p.m.	19°	7	+ 2	— 7	— 5
3	,, 7th	3.15 p.m.	18°	8	+ 3	— 7	— 5
4	,, 7th	...	18°	47	— 6	—99	— 7
5	,, 9th	9.45 a.m.	13°	57	— 7	—12	— 9
6	,, 9th	2.30 p.m.	19°	31	— 8	—11	— 9
7	,, 9th	4.45 p.m.	19°	77	— 5	—10	— 7
8	,, 9th	4.50 p.m.	19°	76	— 4	— 9	— 6
9	,, 10th	10.30 a.m.	14°	62	— 1	— 5	— 3
10	,, 10th	11.0 a.m.	15°	51	— 1	— 5	— 4
11	,, 10th	11.30 a.m.	17°	35	— 2	— 5	— 4
12	,, 10th	12.30 p.m.	19°	23	— 3	— 7	— 6
13	,, 10th	2.30 p.m.	18°	45	— 2	— 4	— 4
14	,, 10th	3.0 p.m.	15°	50	— 4	— 7	— 7
15	,, 10th	4.0 p.m.	18°	63	— 5	—11	— 8
16	,, 10th	5.15 p.m.	19°	81	— 6	—10	— 8
17	,, 10th	5.35 p.m.	19°	83	— 4	— 8	— 6
18	,, 10th	9.15 p.m.	13°	72	— 3	— 7	—11
19	,, 13th	2.25 p.m.	20°	88	— 7	— 8	— 7
20	,, 13th	3.15 p.m.	20°	77	— 2	— 6	— 6
21	,, 13th	3.45 p.m.	20°	52	+ 1	— 2	— 2
22	,, 13th	4.30 p.m.	21°	30	+ 2	— 5	— 5
23	,, 13th	5.0 p.m.	21°	50	— 2	— 6	— 6
24	,, 13th	5.25 p.m.	21°	79	— 5	—10	— 9
25	,, 14th	9.45 a.m.	15°	83	— 5	—12	—10
26	,, 14th	10.10 a.m.	15°	85	— 5	—11	—10
27	,, 14th	10.35 a.m.	17°	70	— 3	— 7	— 6
28	,, 14th	11.20 a.m.	19°	52	+ 2	— 7	— 6
29	,, 14th	12.0 noon	20°	36	+ 3	— 8	— 7
30	,, 14th	12.30 p.m.	21°	50	+ 1	— 6	— 5
31	,, 17th	9.30 a.m.	13°	73	— 5	—12	— 9
32	,, 19th	11.5 a.m.	18°	89	— 3	—10	— 8
33	,, 19th	11.35 a.m.	18°	67	—11	— 7	— 5
34	,, 19th	12.5 p.m.	19°	45	— 1	— 6	— 5
35	,, 19th	12.30 p.m.	19°	35	— 2	— 6	— 5
36	,, 19th	1.15 p.m.	20°	87	— 3	—10	— 9
The following low temperature readings were taken in Smithfield Cold Stores.							
37	May 20th	3.45 p.m.	—6°	67	—14	—23	—16
38	,, 20th	3.50 p.m.	—6°	67	—12	—22	—16
39	,, 20th	4.10 p.m.	—6°	49	—13	—22	—18
40	,, 20th	4.15 p.m.	—6°	52	—13	—20	—15
41	,, 20th	5.10 p.m.	—5°	31	—11	—13	—13
42	,, 20th	5.20 p.m.	—5°	32	—13	—14	—14
43	,, 20th	6.10 p.m.	—5°	21	—11	—13	—13
44	,, 21st	8.20 a.m.	—9°	28	—15	—17	—17
45	,, 21st	8.25 a.m.	—9°	27	—15	—17	—17
46	,, 21st	9.10 a.m.	—7°	15	—12	—16	—10
47	,, 21st	9.50 a.m.	—5°	30	—12	—13	—14
48	,, 21st	10.0 a.m.	—5°	31	—12	—13	—14
49	,, 21st	10.45 a.m.	—6°	48	—16	—21	—18
50	,, 21st	11.30 a.m.	—5°	60	—12	—20	—15
51	,, 21st	11.35 a.m.	—5°	61	—12	—20	—15

(*Continued on page* xxxvi.)

TABLE X.—*Continued.*

The following low temperature readings were taken in Smithfield Cold Stores—(Continued).

Experiment No.	Date.	Time.	Room temperature.	Humidity by dew-point apparatus.	Correction to mean calibration curve.		
					Hair hygrometer Type A.	Hair hygrometer Type B.	
						No. 1.	No. 2.
52	May 21st	12.0 noon	—6°	59	—14	—19	—14
53	,, 23rd	9.30 a.m.	—7°	87	— 9	—18	—14
54	,, 23rd	9.35 a.m.	—7°	86	— 9	—10	—13
55	,, 23rd	10.25 a.m.	—5°	49	—11	—17	—13
56	,, 23rd	10.30 a.m.	—5°	50	—11	—16	—13
57	,, 23rd	11.10 a.m.	—4°	37	—14	—16	—14
58	,, 23rd	11.15 a.m.	—4°	38	—12	—16	—14
59	,, 23rd	11.50 a.m.	—3°	21	—11	—14	—13
60	,, 23rd	1.45 p.m.	—6°	20	—13	—15	—14
61	,, 23rd	2.30 p.m.	—4°	34	—14	—14	—14
62	,, 23rd	2.40 p.m.	—4°	35	—13	—14	—13
63	,, 23rd	3.30 p.m.	—5°	54	—13	—19	—16
64	,, 23rd	3.35 p.m.	—5°	54	—13	—19	—15
65	,, 23rd	4.20 p.m.	—5°	65	—15	—24	—18
66	,, 23rd	4.50 p.m.	—5°	75	—14	—24	—18
67	,, 25th	9.0 a.m.	—9°	65	—13	—21	—16
		Experiments at Room Temperature.					
68	May 25th	5.0 p.m.	+21°	84	— 5	— 9	— 7
69	,, 25th	5.20 p.m.	+22°	65	— 3	— 7	— 6
70	,, 26th	10.20 a.m.	+20°	47	— 3	— 8	— 7
71	,, 26th	11.10 a.m.	+22°	39	— 4	— 7	— 8
72	,, 26th	12.0 noon	+23°	26	— 2	— 6	— 7
73	,, 26th	12.45 p.m.	+23°	37	— 4	— 0	— 8
74	,, 26th	2.30 p.m.	+21°	49	— 8	—12	—12
75	,, 26th	3.25 p.m.	+23°	64	— 8	—14	—14
76	,, 26th	4.10 p.m.	+22°	76	— 8	—16	—13
77	,, 26th	4.55 p.m.	+21°	78	— 8	—16	—13
78	,, 27th	10.15 a.m.	16°	62	— 7	—14	—12
79	,, 27th	11.10 a.m.	20°	82	— 6	—14	—12
80	,, 27th	12.30 p.m.	21°	62	— 4	— 9	— 9
81	,, 27th	2.20 p.m.	22°	54	— 5	—11	— 9
82	,, 27th	3.10 p.m.	22°	44	— 4	— 8	— 9
83	,, 27th	4.5 p.m.	22°	28	— 4	— 9	— 9
84	,, 27th	4.50 p.m.	22°	45	— 5	— 9	— 9
85	,, 27th	5.15 p.m.	22°	60	—10	—17	—13
86	,, 28th	10.15 a.m.	19°	88	— 3	—10	— 9
87	June 1st	9.45 a.m.	16°	65	— 5	—13	—11
88	,, 1st	10.15 a.m.	18°	52	— 5	—11	— 9
89	,, 1st	11.10 a.m.	20°	46	— 4	—10	— 9
90	,, 1st	11.50 a.m.	21°	31	— 4	— 9	— 9
91	,, 1st	12.30 p.m.	21°	42	— 5	—10	— 8
92	,, 2nd	9.50 a.m.	17°	55	— 6	—13	—12
93	,, 2nd	10.20 a.m.	19°	65	— 8	—17	—14
94	,, 2nd	11.0 a.m.	19°	81	— 5	—13	—11
95	,, 2nd	12.0 noon	22°	61	— 3	—10	—12
96	,, 2nd	12.50 p.m.	23°	45	— 3	— 9	— 9
97	,, 2nd	2.50 p.m.	23°	31	— 3	—10	—10
98	,, 2nd	4.0 p.m.	24°	26	— 4	— 9	—10
99	,, 2nd	5.0 p.m.	25°	45	— 5	—11	—11
100	,, 3rd	9.30 a.m.	18°	55	— 5	—13	—12
101	,, 3rd	10.10 a.m.	19°	67	— 7	—16	—15
102	,, 3rd	10.35 a.m.	20°	75	— 7	—17	—14
103	,, 4th	...	16°	57	— 6	—14	—13

When the hair hygrometers were placed in the apparatus, and subjected to very low humidities of the order of 5 per cent. a permanent change occurred and the calibration curve shifted in a direction which indicated that the hairs had stretched permanently. The same change, but not to the same extent, occurred in all the hair hygrometers tested.

One of the curves for an instrument type B are reproduced in Fig. 14. The change in the instrument type A (illustrated in Fig. 12) was 3 to 4 per cent. throughout the scale. The calibration curves of the two instruments of type B (illustrated in Fig. 13) changed by 5 and 8 per cent. respectively.

The calibration points repeated themselves, and there was no evidence of appre-

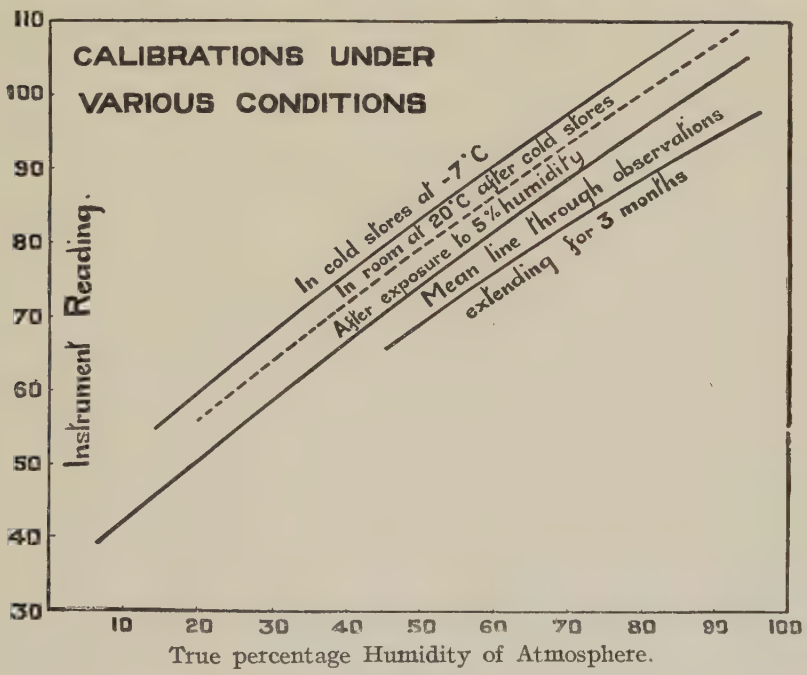

FIG. 14.

ciable hysteresis effect. The data for these experiments are summarised in Table X. (May 7th to 19th).

(*c*) *Calibration at Low Temperatures.*

The next series were made in a cold store at a temperature of about —7°C., the same apparatus being employed. This was then taken to the Central Meat Markets Store at Smithfield, and the calibration repeated at low temperatures.

Comparing the results obtained in the cold stores with the previous ones at room temperature it will be seen that the calibration curve at low temperature for type A has shifted by 8 to 9 per cent.; for type B, No. 1, 10 to 13 per cent., and for No. 2 9 per cent.

On the return of the apparatus to the laboratory the experiments were repeated at room temperature. The results show that instrument type A repeated its original room temperature calibration within the limits of the error of experiment. But

a permanent alteration had occurred on exposure to low temperatures with instruments type B resulting in their calibration curves being displaced (*see* Fig. 14). These results indicate that subjection to extremes of temperature or humidity causes a permanent "set," but for moderate variations of the conditions the instruments behave fairly satisfactorily.

So far as we could ascertain the only difference between types A and B was that the hairs in B were under greater tension than in A.

(*d*) *Influence of Change of Temperature from* 16°C. *up to* +38°C. (60°F. *to* 100°F.).

In these experiments the temperature was varied in steps up to 38°C., while the indications of the instruments were kept at a fixed value by adjusting the moisture content of the atmosphere. The corresponding humidity was determined by the dew-point apparatus. The data obtained are summarised in Table XI., and graphically in Fig. 15. The first exposure of the hairs to higher temperatures on

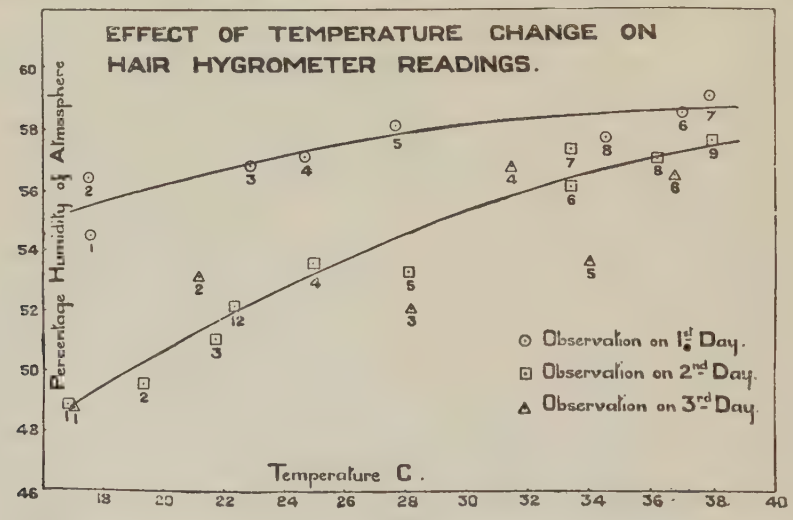

FIG. 15.

June 8th gave results which indicate a slight contraction of the hairs with increasing temperatures. That the change is in this direction will be seen by consideration of the fact that the humidity of the surrounding atmosphere had to be raised as the temperature was raised, and the effect of an increase in the humidity of the surrounding atmosphere is to cause a lengthening of the hairs. In the present experiment the lengthening due to increasing the humidity counteracted the contraction due to temperature.

When repeating the observations the next day, June 9th, the surprising result was obtained that the hairs had taken a permanent set overnight in the direction of expansion; the change amounting to 6 per cent. since the period of exposure to the higher temperatures. It now required only 49 per cent. relative humidity of the atmosphere at a temperature of 16°C. to give the same instrument reading as on the previous day was equivalent to 55 per cent. relative humidity of the atmosphere. The results on this day and the succeeding day show a well-marked coefficient of *contraction* with temperature, the magnitude of which is 0·4 per cent. relative humidity

per 1°C. It is interesting to note that the *expansion* on exposure to cold stores' temperature works out to be practically the same in numerical value as the contraction on exposure to higher temperatures—*i.e.*, an average change of 10 per cent. in the humidity scale for a lowering of 25 deg. in temperature. This gives a coefficient of 0·4 per cent. relative humidity per 1°C.

TABLE XI.—*Influence of Temperature on Indications of Hair Hygrometers.*

(Humidity of atmosphere varied to maintain instrument readings at steady value.)

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	
No. of Experiment.	Temperature of atmosphere.	Dew Forms.	Dew disappears.	Dew-point temperature.	Humidity.	Hair Hygrometer. Type A.	Hair Hygrometer. Type B.	
							No. 1.	No. 2.
June 8, 1921.								
1	17·6	8·0	8·5	8·2	54·3	63·5	77·5	85·1
2	17·6	8·6	8·9	8·7	56·2	64·5	78·0	86·0
3	22·8	13·6	13·7	13·6	56·5	63·5	77·5	85·1
4	24·7	15·3	15·7	15·5	56·8	63·5	77·3	85·1
5	27·7	18·4	18·7	18·6	57·8	63·5	77·5	85·0
6	37·2	27·6	27·8	27·7	58·5	63·5	77·5	85·2
7	37·9	28·5	28·6	28·5	58·9	64·5	77·5	86·0
8	34·6	25·0	25·1	25·0	57·5	63·5	77·0	85·6
June 9, 1921.								
1	16·7	5·5	6·2	5·8	48·8	63·5	77·8	85·8
2	19·4	8·5	9·2	8·8	49·5	63·4	77·7	85·5
3	21·8	10·8	11·5	11·1	50·9	63·5	77·8	85·6
4	25·0	14·6	15·0	14·8	53·4	63·5	77·9	85·6
5	28·2	17·7	17·8	17·7	53·2	63·5	77·7	85·5
6	33·4	23·4	23·5	23·4	55·9	63·5	77·5	85·4
7	33·4	23·8	23·8	23·8	57·1	63·5	77·2	85·2
8	36·3	26·3	26·5	26·4	56·7	63·5	77·7	86·0
9	38·2	28·2	28·4	28·3	57·4	63·9	76·3	84·5
	The following three observations were taken directly after cooling down.							
10	24·2	14·8	15·0	14·9	56·3	63·6	77·8	85·6
11	22·9	12·7	13·0	12·8	56·4	63·5	76·8	85·0
12	21·7	11·2	11·6	11·4	52·1	63·5	77·2	85·3
June 10, 1921.								
1	16·5	5·3	6·0	5·6	48·7	63·5	77·5	
2	22·2	11·1	11·3	11·2	49·9	63·5	77·5	
3	28·3	17·3	17·5	17·4	51·8	63·5	77·2	
4	31·5	21·7	22·0	21·8	56·6	63·5	77·5	
5	35·1	24·3	24·3	24·3	53·6	63·6	77·5	
6	36·8	26·5	26·9	26·7	56·3	63·5	77·3	

The experiments show that the instrument has a true thermal contraction or expansion with increasing or decreasing temperatures.

The most serious defect of this type of hygrometer is the permanent changes on

exposure for the first time to big fluctuations of temperature or humidity resulting in elongation of the hairs. It is very curious that the change should always occur in this direction, and it may possibly be due to the fact that the hairs are always under tension by the control springs.

(*e*) *Accuracy of the Engraved Scale Supplied with the Instruments.*

It was somewhat disconcerting to find the scales supplied with the instruments of types A and B to be so much in error. Even when the pointers were adjusted to read correctly at one point of the scale the divergence at the extreme end amounted to as much as 30 per cent. (*See* Table XI.)

This wide discrepancy was traced to the fact that the maker had attempted to obtain the scale by comparison with a wet and dry bulb thermometer of the non-ventilated type.

Recently we obtained from another source an instrument somewhat similar to type A (Fig. 12), but with gravity instead of spring control. On testing this instrument at room temperature over the range 50 to 100 per cent. humidity, the maximum error only amounted to 3 per cent.

(*f*) *The Relation between the Extension of the Hairs and the Relative Humidity of the Atmosphere.*

The relation between the linear expansion of the hairs and the relative humidity is given in Table XII.

TABLE XII.—*Relation between Extension of Hairs and Relative Humidity of Atmosphere.*

Relative humidity of atmosphere.	Percentage extension of hairs.
10	0·40
20	0·67
30	0·91
40	1·11
50	1·29
60	1·45
70	1·58
80	1·70
90	1·81

These data have been obtained from the measurement of the lever system of one of the instruments (type B) and the experimental data connecting the angular deflection of the pointer with the relative humidity.

In view of the complex structure of the hair it is hardly to be expected that the same relationship will rigorously apply to all instruments of this type.

(*g*) *Summary of Conclusions Concerning Hair Hygrometers.*

From the results of the experiments one arrives at the conclusion that, under normal working conditions and subjected to ordinary variations of humidity and temperature, the hair hygrometer shows a tendency to give high readings with lapse of time. This may be due to the fact that the hairs are always under tension, and consequently a permanent set takes place.

In our experience the instruments which behave most satisfactorily are those in which the tension force is small and whose bearings and pivots are so well made that friction is a minimum. There is no doubt that good performance from the hair hygrometer can only be obtained when the design of the instrument is such that the hairs are safeguarded from any undue strain.

The instrument should not be subjected to large variations of temperature, and the calibration should be checked at frequent intervals under conditions identical with those under which it is used.

The presence of oil vapour in the atmosphere and of dust is stated to reduce with time the sensitivity of the hairs by preventing free access of the aqueous vapour to the surface, and precautions should therefore be taken to eliminate these disturbances as much as possible.

(*h*) *Distant Reading Form of Hair Hygrometer.*

The hair hygrometer is the simplest of all instruments to convert to a distant reading type. We constructed a distant reading instrument of the form shown in Fig. 16. It is a standard form of recording hair hygrometer with the clockwork

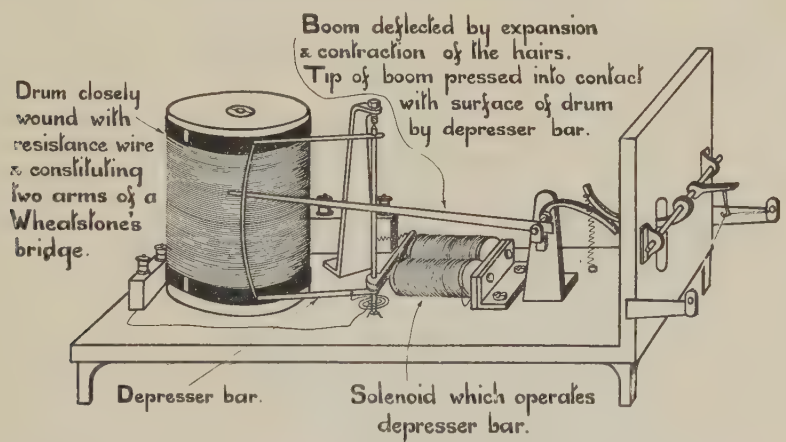
Boom deflected by expansion & contraction of the hairs.
Tip of boom pressed into contact with surface of drum by depresser bar.
Drum closely wound with resistance wire & constituting two arms of a Wheatstone's bridge.
Depresser bar.
Solenoid which operates depresser bar.

FIG. 16.

drum removed and replaced by a stationary drum wound with oxidised wire giving a total resistance of 1,000 ohms. A longitudinal strip is cleaned on the surface of the drum so that electrical contact can be effected with the wire. The pointer has a silver contact piece instead of the pen. Above the pointer is fixed a " chopper bar " arrangement operated by an electro-magnet. When a reading of the humidity is desired the observer switches on the electro-magnet which brings the pointer into contact with the drum immediately beneath the spot where it is situated.

The resistance drum then constitutes the two arms of a Wheatstone's bridge and the pointer is the contact to the galvanometer circuit ; the other galvanometer contact is on a similar drum at the observation station. The observer balances the bridge in the usual manner and thus determines electrically the position of the pointer on the drum which is situated at the hair hygrometer.

The behaviour of the instrument was found to be quite satisfactory over a

long period of test, but it suffers, of course, from all the inherent defects associated with the use of hair as a fundamental element in the design of a physical instrument.

6. Thermal Effect on Cotton Hygrometer.

Orme Masson* in 1904 investigated the change in temperature produced in dry cotton wool when exposed to a damp atmosphere. He employed a mercury thermometer with about 1 gram of cotton wool wound around the bulb and observed the temperature rise when the instrument was withdrawn from a desiccator to a humid atmosphere.

His experiments showed that the heat production was proportional to the amount of hygroscopic absorption. He suggested the possibility of utilising the phenomenon

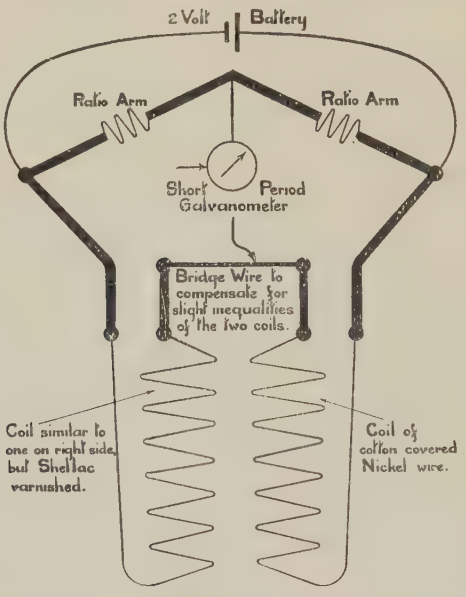
2 Volt Battery
Ratio Arm
Ratio Arm
Short Period Galvanometer
Bridge Wire to compensate for slight inequalities of the two coils.
Coil similar to one on right side, but Shellac varnished.
Coil of cotton covered Nickel wire.

Fig. 17.

as a method of measuring humidity, but did not give this aspect of the subject detailed investigation.

Drs. Chattock and Tyndall modified Masson's arrangement by employing thermo-junctions instead of mercury thermometers. By this device they were able to reduce the time of exposure required for attaining the maximum temperature to 15 seconds and the period of drying out to half an hour. In Masson's experiments the maximum temperature was not attained below a period of about 5 minutes and the drying out occupied about 24 hours.

Drs. Chattock and Tyndall found that the "constant" of their instrument varied in an inexplicable manner and the changes were of such a magnitude as to render the instrument of little value as a hygrometer. They brought the subject

* Proc. Roy. Soc., Vol. LXXIV., p. 230 (1904). Masson and Richards, Proc. Roy. Soc., Vol. LXXVIII., p. 412 (1906).

before the Engineering Committee of the Food Investigation Board, who requested that the matter should also be investigated further at the Laboratory as the method seemed to have possibilities as the basis of the design of a distant-reading hygrometer.

(*b*) *Electrical Resistance Type.*

After consideration of the magnitude of the temperature changes to be observed we decided to abandon the use of thermo-junctions in favour of a resistance thermometer method. This had the additional advantage that the absorbent cotton was distributed evenly over a length of wire instead of being concentrated in a blob around the thermo-junction.

Accordingly a differential resistance thermometer was made of cotton covered nickel wire wound on a large ebonite rack similar to a resistance thermometer. On one of the coils the cotton covering was left in its natural state, whilst that on the other was shellac varnished. These coils were connected up in the form of a Wheatstone's bridge and the arrangement of the coils is shown in Fig. 17. Each coil was composed of about 15 feet of wire of approximately 22 ohms resistance. The mean temperature coefficient of resistance between 0°C. and 100°C. was 0·00516 per 1°C.

The function of the varnished coil is to compensate for changes of resistance of the cotton covered coil due to changes of room temperature, so that the bridge

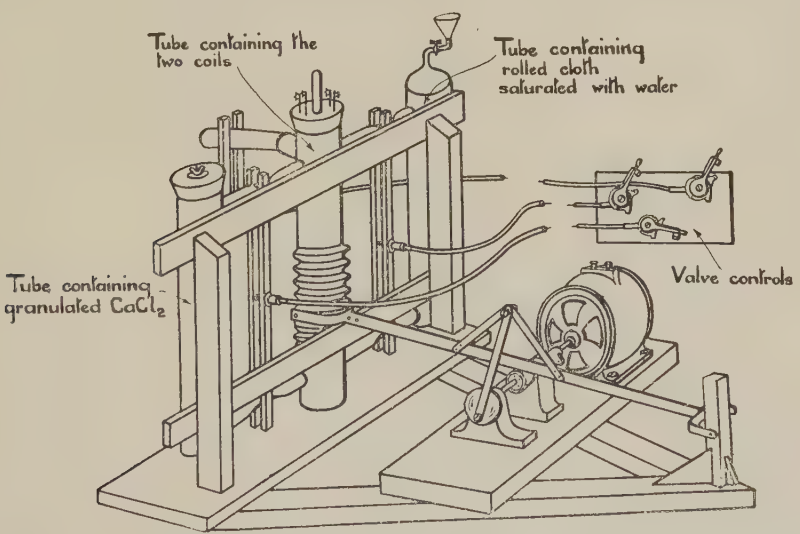
Tube containing the two coils
Tube containing rolled cloth saturated with water
Valve controls
Tube containing granulated $CaCl_2$

FIG. 18.

is balanced at all temperatures. If the coils are placed in a dry atmosphere, then on exposure to a humid atmosphere a large deflection of the galvanometer spot is obtained, due to the ready absorption of water vapour by the untreated cotton on the one coil.

The thermal effect on absorption of water vapour occurs with extraordinary rapidity, the maximum deflection being attained within 6 seconds of the exposure. In order to slow down the effect six additional layers of cotton were wound on the wire, bringing up the external diameter to approximately one millimetre, the diameter

of the nickel wire being only one tenth of a millimetre. This increased the time taken to reach a maximum to about 12 seconds.

With the means at our disposal it was not possible to wind the additional layers of thin cotton so closely and well spaced as to give a perfectly even surface, and consequently it presented a slightly corrugated appearance. This may be an advantage, as it helps to expose more surface to the atmosphere. Having satisfied ourselves that the instrument would work at temperatures below 0°C. experiments were made at room temperatures so as to obtain some information as to the characteristics of the phenomenon.

In the early experiments the coil was carried from a rubber stopper which

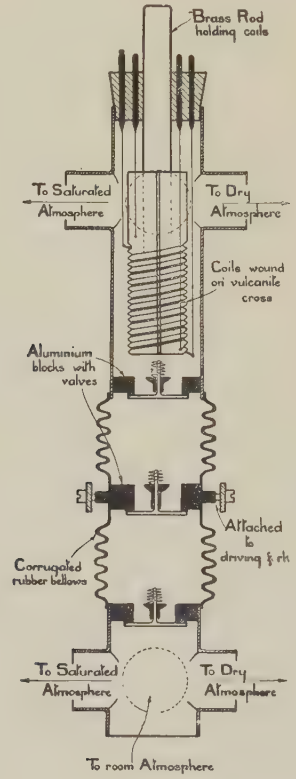

FIG. 19.

could be inserted into wide mouthed bottles containing a dry or a saturated atmosphere. The coil when transferred from the dry to the saturated atmosphere would give consistent readings, but these were quite valueless owing to the fact that the coil absorbed the moisture in its vicinity, and the effect of such absorption was to upset completely the hygrometric conditions of the atmosphere in the vessel.

(*c*) *Apparatus utilising the Effect for Hygrometric Measurements.*

To overcome these difficulties the form of apparatus, shown diagrammatically in Fig. 18, was devised. The coil is contained in the central tube and past it is pumped either dry air from the tower on the left, saturated air from the tower on

the right, or air from the room through an inlet and outlet in front. The pumping device is a corrugated rubber tube made from a motor tyre and it contains three disc valves of large diameter as shown in Fig. 19. This method of pumping was adopted in preference to the usual type of piston in order to avoid the necessity of introducing any lubricant between a piston and cylinder which might be carried on to the coil by the air stream, also all generation of heat by friction between moving parts is eliminated. Connections between the towers are made by $1\frac{3}{4}$-inch bore rubber tubing and both inlet and outlet to a tower can be closed by one movement of a spring-operated crossbar. The general features of the apparatus will be understood from the diagrams. The drying tower contains granulated calcium chloride, while the saturation tower is filled with a roll of brass gauze and muslin interwoven, which is periodically saturated with water.

The procedure in taking the observations is as follows: The tower containing

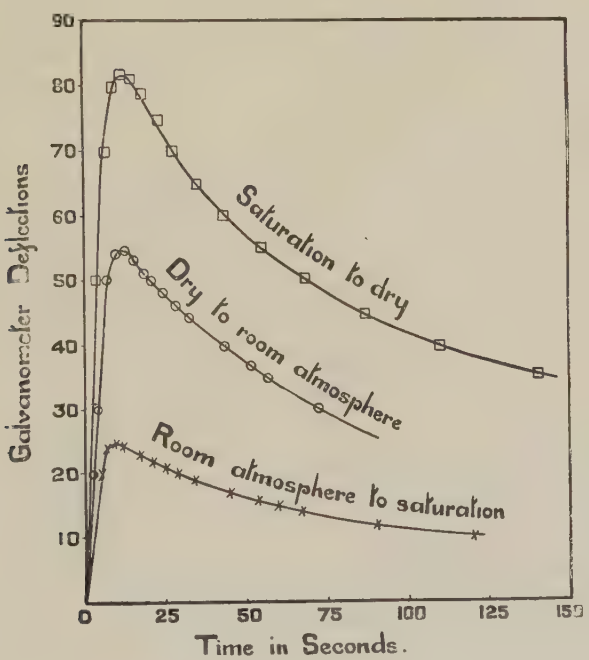

FIG. 20.

the coil is placed in communication with the drying tower and air pumped around for a few minutes. The inlet and outlet to the atmosphere of the room is then opened quickly and the drying tower cut off. A typical time-deflection curve for the galvanometer spot is shown in Fig. 20, the maximum deflection corresponding to a temperature change of 2·7°C. When the galvanometer spot has returned to nearly zero the communication with the saturation tower is quickly opened and that to the atmosphere of the room closed. A similar form of curve is obtained.

Finally the saturation tower is cut off and communication made to the dry tower. The deflection will now be in the opposite direction since the cotton is being subjected to a dry atmosphere following a saturated one, and is consequently

liberating moisture. Any one of these operations can be carried out in the reverse direction with practically identical results.

Since the natural period of the moving coil system of the galvanometer is a fifth of a second, it closely follows the change of resistance of the coil. It will be observed that the sum of the maximum deflections obtained on exposure from " dry to room " and " room to saturation " successively is nearly equal to the maximum deflection obtained on going direct from " saturation " to " dry."

The direct transfer gives a slightly larger deflection, owing presumably to the smaller loss of heat during the time it is rising to a maximum. The actual magnitude

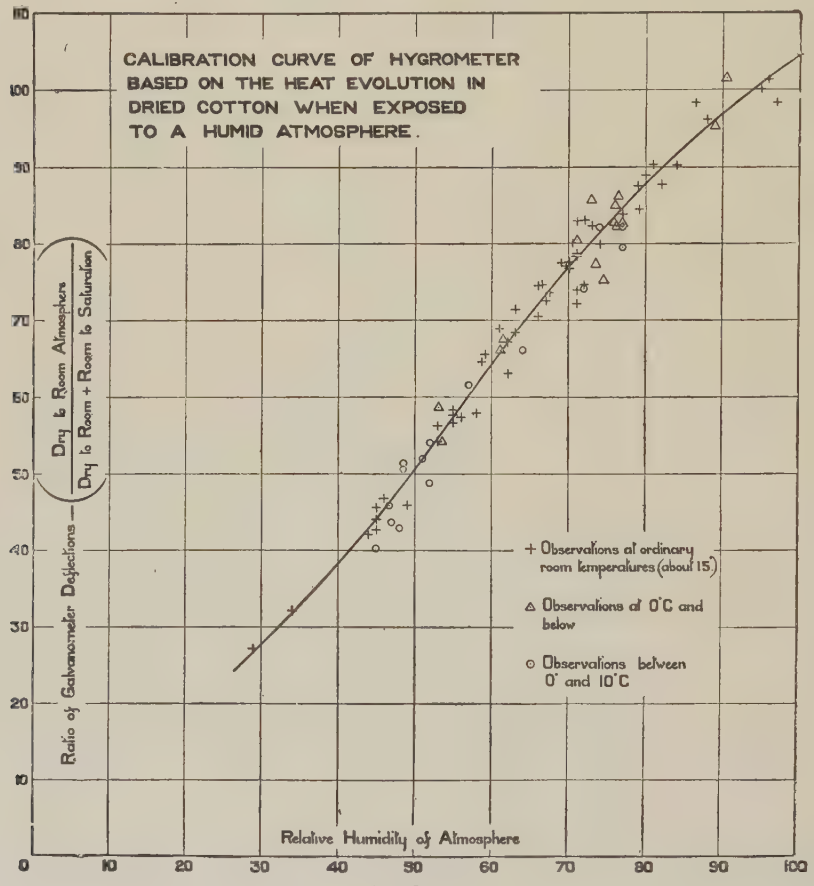

FIG. 21.

of the deflection obtained depends upon several factors besides the relative humidity, such as the temperature of the air, velocity of the circulating air stream, galvanometer sensitivity, and the battery current. It was found, however, that the percentage deflection, *i.e.*, ratio of {(Dry to Room)/[Dry to Room+Room to Saturation]} was independent of all the above variables, and (within the limits of the errors of experiment) a function of the relative humidity alone (*see* Table XIII. and Fig. 21).

This procedure in taking the observations was found to be much more convenient

TABLE XIII.—*The Thermal (Cotton) Hygrometer.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
Date.	Time.	Temp. room.	Humidity by psychrometer.	Humidity by dew-point apparatus.	Mean humidity.	Deflection :— Dry to room atmosphere.	Deflection :— Room atmosphere to saturation.	Sum of dry to atmosphere + atmosphere to saturation.	Deflection :— Saturation to dry.	Ratio :— Dry to atmosphere / Dry to atmosphere + atmosphere to saturation.	Difference from Mean curve through observations.
1920.											
Oct. 15	10.42 a.m.	15°	82	...	82	67·8	9·5	77·3	71·5	87·7	—2·3
,, 20	9.31 ,,	12°	68	...	68	56	...	...	82	...	...
,, 20	11.50 ,,	13·7°	63	...	63	54·5	25	79·5	82	68·5	0
,, 21	10.26 ,,	10·5°	72	...	72	53·8	18·8	72·6	75	74·1	—5·4
,, 25	4.44 p.m.	15·6°	70	72	71	52	20	72	71	72·2	—5·8
,, 25	9.15 a.m.	15°	57	59	58	40	29	69	71	58	—3·5
,, 26	10.54 ,,	17°	54	58	56	44	32·5	76·5	80	57·5	—1·5
,, 26	2.37 p.m.	23·5°	96	98	97	110	18	128	96	98·4	—4·1
,, 27	3.33 ,,	15°	69	71	70	56·5	17	73·5	71	76·9	—0·1
,, 28	11.40 a.m.	15°	65·5	66·5	66	48	20	68	69·8	70·6	—1·4
,, 28	4.34 p.m.	23°	100	100	100	110	—5	105	88	104·7	+0·2
,, 29	11.45 a.m.	14°	67	67	67	45·5	17·2	63	66·2	72·6	—0·9
,, 29	3.49 p.m.	16°	62	...	62	42·8	25	67·8	69·3	63·1	—3·9
,, 30	7.30 ,,	14°	55	55	55	40	30·5	70·5	68·8	56·7	—0·8
,, 31	6.30 ,,	12°	71	71	71	50·6	13·7	64·3	63·1	78·7	+0·7
Nov. 1	3.30 ,,	10°	79	75	77	50·4	13	63·4	59	79·5	—5·5
,, 1	8.30 ,,	9°	79	75	77	46·6	10·1	56·7	54·5	82·2	—2·8
,, 2	4.55 ,,	9°	...	46·7	...	23·2	27·3	50·5	54·7	45·9	—0·6
,, 3	12.30 ,,	13°	...	28·8	...	13·6	36·5	50	53·5	27·1	+0·1
,, 3	4.50 ,,	15°	...	34	...	19	40	59	62·5	32·2	+0·2
,, 6	11.30 a.m.	0°	76	73	74·5	22·8	7·5	30·3	31	75·3	—6·7
,, 6	12.45 p.m.	0°	75	72	73·5	24	7	31	29·7	77·4	—3·6
,, 9	3.0 ,,	—1°	75	79	77	24·3	5	29·3	29·4	82·9	—2·1
,, 15	2.30 ,,	0°	77	75	76	27·8	4·9	32·7	32·5	85	+1
,, 25	11.0 a.m.	—3°	78	74	76	24	5	29	26·5	82·8	—1·2
,, 27	10.30 ,,	—4°	74	72	73	20·8	3·5	24·3	24	85·6	+5·1
Dec. 2	12.30 p.m.	—1°	76	73	74·5	25·2	8	33·2	29·8	75·9	—6·1
,, 3	9.45 ,,	—1°	79	74	76·5	25	4	29	27·5	86·2	+2·2
,, 6	...	—2°	78	75	76·5	22·4	4·8	27·2	27	82·3	—1·7
1921.											
Jan. 24	...	15°	71·7	71	71	51	10·4	61·4	60	83	+5

,,	22	11.30	,,	12°	69	68·6	69	43	12·5	55·5	56·6	77·5	+1·9
,,	22	11.30	,,	12°	69	68·6	69	43	12·5	55·5	49·5	66·1	—3·9
,,	26	11.20	,,	10°	63·5	64·1	64	33·2	17	50	49	61·6	+1·1
,,	28	5.0	p.m.	9°	56·5	57·3	57	29	18·1	47	42·3	54·1	+0·6
Mar.	2	12·40	,,	6°	52·5	51	52	23	19·5	42·5	42·5	50·6	+1·9
,,	3	12·35	,,	6°	49·5	47·5	48·5	21	20·5	41·5	42	51·4	+2·7
,,	3	5.0	,,	7°	49	48	48·5	22	20·8	42·8	52	46·9	+1·4
,,	4	5·0	,,	13°	46	46	46	24·3	27·5	51·8	53·5	44	0
,,	5	12.30	,,	14°	45	45	45	24	30·6	54·6	49·2	45·6	+1·6
,,	7	12.30	,,	12°	45	45	45	22·3	26·6	48·9	51·2	42·1	—0·9
,,	7	5.0	,,	13°	44·1	44	44	22·5	31	53·5	47	40·3	—3·7
,,	8	12.45	,,	9°	46	44	45	18·9	28	46·9	41	43·8	—3
,,	8	5.0	,,	7°	47	47	47	18·2	23·4	41·6	36·7	48·9	—4·5
,,	9	5.0	,,	4°	52·5	51	52	18·2	19	37·2	37·5	43	—5
,,	10	5.0	,,	4°	48	48	48	16	21·2	37·2	34	52	0
,,	11	12.30	,,	3°	52	50	51	18·5	17	35·5	31·7	54·4	—1
,,	11	5.0	,,	0°	55	52	53·5	16·7	14	30·7	28·7	66·3	+0·3
,,	12	9.30	a.m.	—1°	64	58	61	17·7	9	26·7	29	58·8	+4·3
,,	12	12.45	p.m.	0°	54	52	53	16·4	11·5	27·9	28·8	95·3	—0·7
,,	12	4.0	,,	0°	89	89	89	30·2	1·5	31·7	56·4	87·5	+0·5
,,	14	5.0	,,	12°	79	79	79	53·8	7·7	61·5	54·5	83·1	+3·6
,,	15	12.30	,,	12°	72	72	72	46	9·3	55·3	56·5	82·4	+1·9
,,	15	5.0	,,	13°	73	73	73	47	10	57	84·3.	81	+0·5
,,	16	12.40	,,	12°	72	74	73	46·8	11	57·8	59·6	78·5	+0·5
,,	16	5.10	,,	14°	71	71	71	49	13·4	62·4	52	80·2	+2·7
,,	17	12.40	,,	12°	70·5	70·7	70·6	43·5	10·7	44·2	57	90·3	—1·4
,,	17	5.0	,,	14°	84	84	84	56	60	116	57·7	84·5	—2·5
,,	18	12.35	,,	14°	78·5	79·8	79·2	51·8	9·5	61·3	64	96·2	+1·2
,,	18	5.0	,,	15°	88	87·4	87·7	63·5	2·5	66	59·5	98·3	+4·3
,,	19	12.35	,,	15°	86·5	86·5	86·5	60	1	61	58·5	89	+1
,,	21	5.0	,,	15°	80	80	80	55	6·8	61·8	60	90·4	+1·4
,,	22	12.30	,,	16°	82	80	81	56·4	6	62·4	61·5	73·7	—0·3
,,	22	5.0	,,	15°	68	67	67·5	45·8	16·3	62·1	30·4	67·5	+1
,,	31	4.50	,,	—1°	63	60	61·5	22	10·6	32·6	31·2	93·9	+9·1
Apr.	1	12.30	,,	0°	78	76	77	21·3	1·9	23·2	31·2	101·5	+4
,,	1	5.0	,,	0°	92	89	90·5	33·7	—5	28·7	28·5	80·4	+2·4
,,	2	12.30	,,	—2°	72	70	71	23	5·6	28·6	63·2	77·5	+0·5
,,	11	5.0	,,	15°	71·5	68·5	70	48·3	14	62·3	48·2	74·6	+2·3
,,	14	5.0	,,	14°	66	...	66	42·7	14·5	57·2	52·2	69	+3
,,	20	5.0	,,	12°	62	60	61	36	16	52	51·3	71·5	+3
,,	21	12.30	,,	12°	63·5	62·5	63	36·5	14·5	51	56	65·7	+2·7
,,	21	5.0	,,	14°	60	58	59	36·5	19	55·5	57	74·6	+2·1
,,	22	5.0	,,	15°	67	65·6	66·3	44	15	59			

[*To face page* xlvi.

than attempting to find a "constant" for the instrument, since it reduces the work to merely observing deflections of the galvanometer spot, and the instrument is self calibrating once the form of the curve connecting deflection ratios to true humidity has been determined.

Several features of the curves shown in Figs. 20 and 21 deserve attention. An analysis of the data in Fig. 20 indicates that the rate of cooling is not proportional to the temperature excess : the heat loss is very rapid initially, and then slows down considerably. In fact it seems that the cotton continues to absorb moisture, thus generating heat, for a considerable time after the maximum effect has been observed. The same applies to the drying out when exposed to air which has circulated through the $CaCl_2$ tower. Hence it is difficult to calculate the correction for the heat loss during the period the deflection is rising to a maximum. The problem is further complicated by the fact that the observed temperature is that of the wire core, and this may differ appreciably from that of the cotton surface in contact with the air stream. Cotton is a complex organic material concerning which very little is known.

It is probable that the form of the curve shown in Fig. 21 is determined to some extent by the mechanical details of the apparatus. In the ideal case one would expect that the quantity [(Dry to atmosphere)/(Dry to atmosphere+Atmosphere to saturation)] would be proportional to the relative humidity.

When the atmosphere of the room is near saturation one finds that the deflection obtained on exposure of the dry cotton to the atmosphere is equal to or slightly greater than that obtained when the dry cotton is exposed to the air circulated from the "saturation" tower. This is probably due to the fact that the air coming into contact with the resistance coil from the "saturation" tower is below room temperature. When the humidity of the room atmosphere is raised by blowing steam into the air, the temperature rises quite considerably, and it is to be expected that the temperature of the layer of muslin within the saturation tower would lag behind that of the room.

Further the action of the pumping arrangements tends to produce rarefaction of the air being circulating if there is any resistance to its flow. The conclusion one arrives at after an extended experience with the apparatus is that it is very difficult to obtain results with it when the humidity of the atmosphere is near saturation.

It is conceivable that by further improvements in construction these defects may be remedied.

7. The Hot Wire Hygrometer.

Our attention has frequently been drawn to the possibility of applying the hot-wire method for measuring humidity.

Instruments utilising the fact that the thermal conductivity of the surrounding gas determines the heat loss from a wire, under appropriate conditions, have found extensive application as hydrogen and carbon dioxide recorders.

The method is an extraordinarily sensitive one for hydrogen-air mixtures since the thermal conductivity of hydrogen is nearly six times that of air. Koepsel* states that his apparatus is capable of easily detecting the presence of 0·001 per cent. of hydrogen without the use of a very refined measuring apparatus.

* Ber. physik. Ges. **10**, p. 814 (1908).

During the war Dr. Shakespear* made a portable instrument termed the "Katharometer" for measuring the permeability of balloon fabrics to hydrogen, and his instrument has been applied to a variety of uses.

The katharometer and CO_2 recorders are manufactured commercially by the Cambridge & Paul Instrument Co.

We are not acquainted with the results of any experiments on the thermal conductivity of water vapour air mixtures, but from some data we estimated that the effect of the change from absolute dryness to saturation of air at —10°C. would be to increase its thermal conductivity by 8 parts in 10,000.

As it is desirable to measure humidities to an accuracy of 1 per cent. this will necessitate the measurement of thermal conductivity changes to a few parts in a million.

We inquired of the Cambridge & Paul Instrument Co., what order of deflections they considered possible with their hot-wire instruments in hygrometric measurements. They stated that at room temperature with a totally suspended type of indicator it would be possible to obtain full scale deflection for 100 per cent. humidity, but at —10°C. the deflection would be about 14 millimetres, and with a recorder half this amount.

This decrease in sensitivity is due to the fact that the deflection depends upon the actual weight of vapour present in the air, and not its relative humidity.

A full scale range of 14 millimetres would not give sufficient accuracy in hygrometric measurements, so it would be necessary to increase it either by the use of a more sensitive indicator or by raising the temperature of the hot wire.

Increasing the galvanometer sensitivity usually results in unstable zero, and increasing the temperature of the wire gives rise to convection currents. So the problem resolves itself into making very accurate resistance measurements when the wire and its insulation are exposed to a humid atmosphere.

One of the troubles of low-temperature work is the frequent deposition of dew, due to temperature changes causing supersaturation, and the formation of a moisture film on the electrical insulation of the wire would be fatal to reliable measurements.

There is also the additional complication of the presence of varying amounts of CO_2 in the atmosphere of the stores. It is a well-known fact that apples, &c., give off CO_2, and the modern method of storage is to seal the room and allow the CO_2 content to rise to 10 per cent. at the expense of the oxygen. Now it appears that volume for volume CO_2 has a greater effect on the thermal conductivity of the atmosphere than H_2O vapour. So to eliminate this variable it would be necessary to employ an absorbent for CO_2 leaving the water vapour.

The writer is not acquainted with any absorbent for CO_2 which will not absorb H_2O at the same time. The alternative method is to estimate by difference: determine the conductivity of the air containing CO_2 and the water vapour; then saturate and again find the conductivity.

It must not, however, be concluded that the hot-wire method has no applications in hygrometry. It is conceivable that it will prove to be of great service for humidity measurements at temperatures beyond the range of the classical methods, since the instrument measures the actual percentage of vapour present, and its sensitivity as a hygrometer will increase with temperature at about the same rate as the saturation vapour pressure.

* Proc. Phys. Soc., Vol. XXXIII., p. 168 (1921).

ACKNOWLEDGMENTS.

The work described in this Paper constitutes a part of a more extensive research carried out on behalf of the Food Investigation Board of the Department of Scientific and Industrial Research.

To the Chairman of the Engineering Committee, Sir Alfred Ewing, and the Chairman of the Insulation Sub-committee, Sir Richard Glazebrook, the author wishes to record his thanks for their continued interest in the work.

The Director of the Laboratory, Sir Joseph Petavel, has furthered the work by placing every facility at our disposal, and by constructive criticism of the various designs.

Mr. W. B. Hardy, Sec. R.S., Director of Food Investigation, has kindly arranged for the blocks for illustrating the Paper to be placed at the disposal of the Society. (The permission of the Controller, H.M. Stationery Office, has been obtained for the reproduction of these illustrations, which are taken from Special Report No. 8 of the Food Investigation Board of the Department of Scientific and Industrial Research, now in preparation.)

Mr. A. Snow, Junior Observer, has rendered valuable assistance with the experimental work, and Mr. Edgar A. Griffiths has suggested many features embodied in the instruments.

THE THEORY OF THE HAIR HYGROMETER.

BY

F. J. W. Whipple, *M.A.*, *F.Inst.P.*

As a practical instrument for the measurement of humidity, the hair hygrometer has many advantages over its rival the psychrometer. Hair hygrometers are in general use in countries where temperature is below the freezing-point for a large fraction of the year, in conditions in which it would be impossible to obtain satisfactory results with the ordinary psychrometer. Moreover, the hair hygrometer lends itself to adaptation as a recording instrument,and as such it is frequently seen in this country. The discrepancies between the humidities shown by hygrometers of different types are often serious, however, and encourage scepticism as to the value of any of them.

The hair hygrometer was first made as an instrument of precision by de Saussure, whose memoir on the subject* appeared in 1783 and is still of great interest. Apparently the theory of vapour pressure had not been developed at the time de Saussure wrote. The "degrees" of his scale were made proportional to the extension of the hair, 0 corresponding with the perfectly dry hair and 100 with the saturated hair, and he investigated the relation between this scale and the vapour density.

The relation between de Saussure's scale and the relative humidity of the air was investigated experimentally by Gay-Lussac. No account of the research is mentioned in lists of Gay-Lussac's works, but the results were communicated to Biot, who incorporated them in his Traité de Physique.† The method adopted by Gay-Lussac was to determine the vapour pressure due to salt solutions or to mixtures of sulphuric acid and water, and to take readings of the hair hygrometer in a close space in presence of such liquids.

Relative Humidity.	Centesimal Degrees of the Hygrometer.		
Per Cent.	No. 44.	No. 5.	No. 68.
0·0	0·0	0·0	0·0
2·1	2·4	2·6	4·6
9·2	14·2	14·5	19·3
13·3	25·3	27·1	30·6
18·9	35·5	36·3	40·0
31·8	51·2	52·9	56·0
35·6	58·5	59·9	61·3
43·7	65·4	66·7	68·0
47·8	71·3	72·1	72·3
54·1	76·8	77·6	78·0
61·9	83·7	83·9	83·2
67·1	87·3	87·7	86·7
77·8	93·4	93·2	91·3
100·0	100·0	100·0	100·0

* Essas sur l'Hygrometrie. Neuchâtel, 1783.

† Paris, 1816. The experiments are described in Vol. II., p. 109; tables are given in Vol. I., p. 532, and in Vol. II., p. 200.

The best-known laboratory experiments on the subject are those of Regnault,* who used solutions of sulphuric acid of various strengths, and developed a normal method in which the air was extracted from the vessel in which the hygrometer was hung up above the acid.

From Regnault we quote the table on preceding page.

This table shows that the results obtained with the two hairs Nos. 44 and 5 were very consistent. The figures referring to hygrometer No. 68 in which the tension applied was greater show considerable departures from those for the other two instruments.

Regnault points out that the zero of the hygrometer scale is not to be trusted, since the reading of the instrument in a perfectly dry atmosphere depends on the time of exposure.

A conspicuous feature of the table is that a variation of humidity of, say, 10 per cent., gives a small change in the length of the hair when it is near saturation, and a large change in a comparatively dry atmosphere. This point is brought out by plotting the results on semilogarithmic paper as in Fig. 2. The change in length corresponding with the change in humidity from 70 to 100 is equal to that corres-

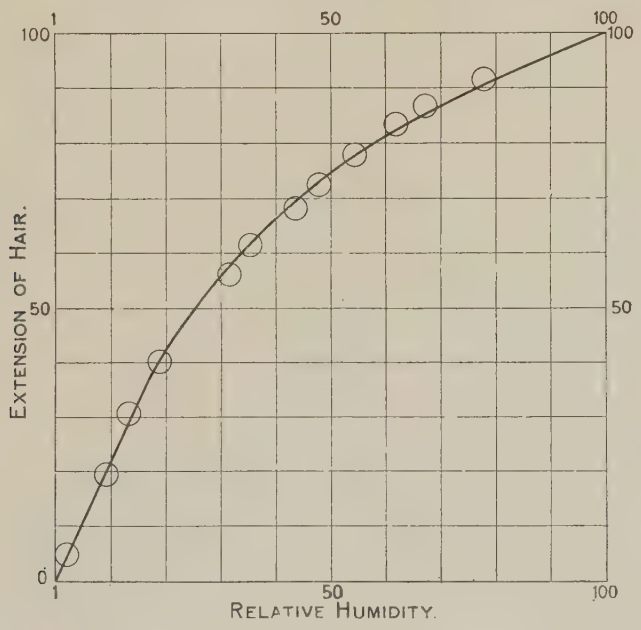

FIG. 1.

ponding with the change from 20 to 30. The graphs (Figs. 1, 2) refer to hygrometer 68, which seems to have been the most satisfactory of the three.

Attempts to express Gay-Lussac's results by empirical formulæ were made by Biot and by Klinkerfuess, but the only theoretical investigation of the phenomena

* Études sur L'Hygrometrie. *Comptes Rendus*, xx., pp. 1127, 1220, Paris, 1845. Reprinted in *Annales de Chimie et de Physique*, xv., p. 129, Paris, 1845. English translation, Taylor's *Scientific Memoirs*, iv., p. 606, London, 1846.

appears to be that of Prof. B. Sresnevsky,* of Moscow. As stated by this author the theory is in some respects incomplete, and the argument has been modified considerably in the following summary.

Microscopic examination of a hair shows that it contains numerous cells; some are filled with colouring matter, whilst others contain more or less water. According to Sresnevsky, when the hair is in a saturated atmosphere these pores are filled to overflowing. On the other hand, in a comparatively dry atmosphere, the water in each cell will be bounded by a curved meniscus. The tendency to reduce the radius of curvature of the meniscus strains the cell walls. (When the hair is saturated, there is no such strain.) It may be expected that, if the cells are elastic and are deformed in accordance with Hooke's law, the contraction of the hair as it dries will be a simple function of the relative humidity.

To determine the conditions in the cells, Sresnevsky makes use of a well-known discussion by W. Thomson (Lord Kelvin) of the way in which vapour pressure in the neighbourhood of a curved meniscus differs from that in the neighbourhood of a plane one. Thomson considered a capillary tube standing in a basin of liquid. In the steady state, there is a difference in vapour pressure at the top of the tube and at the surface of the liquid in the basin. This difference of pressure is due to the weight of the vapour.

In the case dealt with by Thomson the height is small. The pressures are related by the equation

$$p_0 - p_1 = gh\sigma, \quad \ldots\ldots\ldots\ldots \quad (1)$$

where p_0 is the vapour pressure over the liquid in the basin, p_1 the corresponding vapour pressure over the meniscus in the capillary tube, h the elevation in the tube, σ the density of the vapour and g the acceleration due to gravity.

If the height is so great that the differences in the vapour density must be taken into account, Thomson's formula requires modification. If the absolute temperature θ is assumed uniform, and if R is the constant in the equation $p = R\sigma\theta$, then in this more general case it is the equation

$$h = \frac{R\theta}{g} \log \frac{p_0}{p_1}$$

which determines the height to which the column must extend so that the ratio of the vapour pressures at the bottom and top may have a specified value p_0/p_1.

Now if r be the radius of curvature of the meniscus in the capillary tube, T the surface tension of the liquid, P_1 and P_0 the atmospheric pressure on the upper and lower surfaces, and ρ the density of the liquid, assumed uniform, then

$$\frac{2T}{r} = g\rho h - (P_0 - P_1) \quad \ldots\ldots\ldots\ldots \quad (3)$$

The density of the liquid is high compared with that of air, and therefore, $P_0 - P_1$ is small compared with $g\rho h$, so that we have as a good approximation

$$\frac{2T}{r} = g\rho h = R\rho\theta \log (p_0/p_1) \quad \ldots\ldots\ldots\ldots \quad (4)$$

Provided that $g\rho h$ is less than the atmospheric pressure P_0 the whole column in the capillary tube is under hydrostatic pressure, but if $g\rho h$ exceeds this limit the

* Théorie de l'hygrometre à cheveu. Jwijev. Sci. Rep. Imp. Univ., 1895, No. 3.

upper part of the column is in tension, or subject to a negative pressure. This must happen when the capillary is so fine that the rise in the tube exceeds the height of a barometric column of the liquid in question. In the case of water the limit is reached when the radius of the meniscus is about 0·0015 mm., *i.e.*, 1·5μ, so that the diameter of the tube is about 3μ.

For tubes of much smaller microscopic dimensions the height of the column would be far greater than the height of the barometer, and the liquid would be subject to considerable tension or negative pressure. The magnitude of this negative pressure just below the meniscus is given by the equation

$$Q = R\rho\theta \log (p_0/p_1) - P_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The values of Q and r as determined by equations (4) and (5) are shown for water at 283a in the following table, the values assumed for the constants being $\rho=1$, $\theta=283$a, $T=74$ dyne/cm., and $R=4{\cdot}61\times10^6$ C.G.S. The units adopted for the tabulation of r and Q are the millimicrometre (denoted by $\mu\mu$) which is equal to 10^{-9} metre ; and the C.G.S. atmosphere or bar, which is equal to 10^6 dyne/cm.[2]

In these units $Q=3{,}004 \log_{10}(p_0/p_1) - P_0$, whilst $r=1{,}480/(Q+P_0)$.

Relative humidity p_1/p_0.	Negative pressure in the cells Q.	Radius of meniscus r.
99 per cent.	12 bars.	113 $\mu\mu$
95	66	22
90	136	11
80	290	5·1
70	464	3·2
60	665	2·2
50	903	1·6
40	1190	1·2
30	1570	0·9
20	2100	0·7
10	3000	0·5
0	∞	0

The legitimacy of the use of the conception of surface tension in considering a tube whose bore approaches molecular dimensions is more than doubtful, so that too much weight must not be attached to the figures given for r. The values of Q would seem to be more trustworthy.

The very long tube of fine bore is only brought into the argument so that the relations between the curvatures of the meniscus, the internal pressure and the relative humidity may be discovered. The same relations are assumed to hold good when the liquid in a small cell is in equilibrium with the vapour in its neighbourhood.

Sresnevsky applies equation (4) to the problem of the hair hygrometer. His argument is as follows. In the case of a cell with elastic walls the strain exerted by the surface tension of the meniscus tends to contract the cell until the surface tension is in equilibrium with the elastic forces developed by the deformation. Thus the change of volume of the hair depends on the curvature of the meniscus and consequently on the relative humidity of the air. Precision would seem to be gained, however, by basing the argument on equation (5), which indicates that the walls of

the cells are subject to a negative pressure proportional to log (p_0/p_1). If Hooke's law holds, the strain of each cell, and therefore the contraction of the hair as a whole, will be proportional to the same logarithm ; so that the theory leads to the simple result that the contraction of the hair from its length when saturated is proportional to the logarithm of the relative humidity of the atmosphere. The theory should only hold good provided that the drying is not carried so far that many of the cells lose all their water. It is also certain that Hooke's law will not hold in extreme cases.

The agreement of experiment with Srevensky's theory may be judged by the diagram (Fig. 2) in which the contraction of the hair and the relative humidity are plotted on a semi-logarithmic chart, and for humidities above 10 per cent. is as good as could be expected.

As an additional verification that the theory is substantially correct we may compare the stresses which are supposed to be developed in the hair with those which occur when it is stretched by a suspended weight.

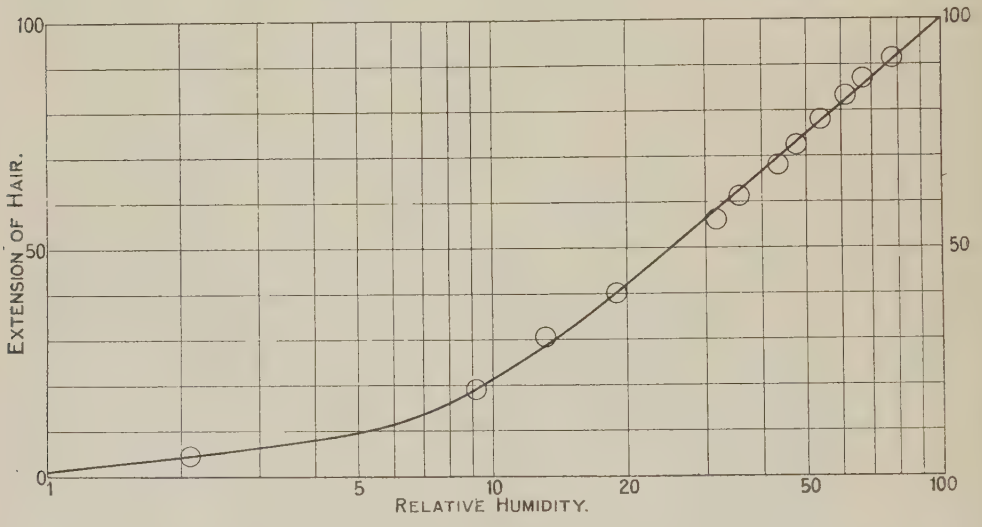

FIG. 2.

To obtain the necessary data* a hair about 22·5 cm. long was mounted vertically so that a lever attached to the lower end could move over a graduated scale, and so that weights could be hung from it. It was found that the extensions due to weight 2 gm., 4 gm. and 10 gm. corresponded with 11, 18 and 36 divisions of the scale respectively, whilst the contraction due to change of relative humidity from 100 to 10 per cent. was 34 divisions. The diameter of the hair was measured and found to be 0·03 mm. It will be seen that the contraction due to drying the hair to relative humidity 10 per cent. was nearly equal to the extension due to a tension of 10 gm. weight, or an average stress of $1{\cdot}4 \times 10^9$ dynes per square centimetre, or 1,400 bar. On the other hand, according to equation (5) the internal stress on the cell walls to produce this contraction should have been about 3,000 bar.

The agreement is not as good as might be hoped for, but it appears that the forces concerned are of the same order of magnitude. The strains in the two cases are

* The observations were made by Mr. H. Fahmy.

evidently of very different characters ; when the hair is stretched by a weight, the cells are elongated, whereas when it shrinks owing to the negative pressure in the cells it is to be presumed that they contract transversely as well as longitudinally.

It is of interest to notice that according to equation (5) the stress in the cells is proportional to the absolute temperature, and the resulting contraction should presumably obey the same rule. Laboratory experiments to decide this point are desirable.

An important application of the theory is that hair hygrometers should not be used in dry atmospheres, where the contents of the hair-cells may completely evaporate. It is well known that in such circumstances the readings are apt to be unreliable. No attempt should be made to carry the calibration of a hygrometer down to very low humidities ; the range from 100 per cent. to 20 per cent. should suffice for almost all purposes.

It is customary to graduate hygrometers so that humidities may be read off at once. For scientific purposes it would, I think, be better to revert to de Saussure's scale, on which equal intervals correspond with equal extensions of the hair ; if the logarithmic law may be assumed, two observations then suffice to calibrate the instrument, and scale readings may be converted to relative humidities by a straight line graph on semi-logarithmic paper. A similar remark applies to hygrographs. The adjustment of the Richard hygrograph is notoriously difficult, and there is, I think, an opening for an instrument in which the displacement of the pen is proportional to the contraction of the hair ; with such an instrument it should be possible to eliminate the zero and scale errors comparatively easily. A station where hair hygrometers are used, *e.g.*, an aeroplane base, should have a pair of Regnault's calibrating vessels giving humidities 100 per cent. and say 30 per cent., and should standardise the instruments as often as necessary. There can be little doubt that for flights above the clouds into regions where temperature is below the freezing point the hair hygrograph is much to be preferred to the psychrometer.

THE RATIONALE OF GLAISHER'S SYSTEM OF HYGROMETRY.

BY

F. J. W. WHIPPLE, *M.A.*, *F.Inst.P.*

BRITISH Meteorology owes a debt to James Glaisher, of the Royal Observatory at Greenwich, for the organisation of climatological observations.

Glaisher attached much importance to hygrometric observations and utilised observations of Daniell's hygrometer to prepare tables for the reduction of dry and wet bulb readings. Most of the observations were taken at the Royal Observatory, Greenwich, from 1841 to 1854; but these were combined with others taken at high temperatures in India, and at low and medium temperatures at Toronto. These tables* of Glaisher's have been in use in the British Meteorological Service for the last 50 years.

If one may judge by the preface to the tables, Glaisher was not guided by theory in the choice of a method of reduction of the material at his disposal. He had to correlate three sets of readings, and adopted the simplest possible type of formula for connecting them. The formula may be written

$$t-t''=k(t-t_w)$$

t being the dry bulb temperature, t_w the wet bulb temperature, t'' the dewpoint, and k a certain factor. Glaisher made the assumption that k was a function of t and independent of t_w. As the observations he utilised in obtaining the appropriate values of k do not appear to have been published in a suitable form we must test them by the work of other investigators, and the simplest way to do this is to refer to tables with a more logical basis that have been published. For this purpose the tables prepared by Hann† are appropriate. Hann uses three formulæ of the type associated with the names of Apjohn, August and Regnault,

$$p_w-p=AP(t-t_w)$$

Here p_w is the saturation pressure at temperature t_w, and p is the actual vapour pressure, whilst P is the atmospheric pressure.

Following Regnault, Hann adopts different values of A according to the strength of the wind blowing on the wet bulb; in the part of his work in which slowly changing factors, which are intended to allow for variations in the latent heat of evaporation, are ignored the values of A are given for the centigrade scale as follows, the values

* *Hygrometrical Tables adapted to the use of the Dry and Wet Bulb Thermometers*, by James Glaisher, F.R.S., &c., London, 1847. No essential changes appear to have been made after the second edition 1856. For the use of computers *Hygrometrical Tables based on Glaisher's Hygrometrical Tables (5th Edition)* were printed by authority of the Meteorological Committee "for private circulation" in 1876, and reprinted in 1904. These tables are designed to reduce the amount of interpolation required with Glaisher's. The Glaisher factors are also given in Marriott's *Hints to Meteorological Observers*, issued by the Royal Meteorological Society in 1881, and in the *Observer's Handbook* of the Meteorological Office, the first edition of which appeared in 1908. The use of Glaisher's method is almost confined to the British Isles.

† Jelineks Psychrometer-Tafeln erweitert und vermehrt von J. Hann; neu herausgegeben und mit Hygrometer-Tafeln versehen von J. M. Pernter. Fünfte erweiterte Auflage, Leipzig, 1903. English authors have usually attributed the psychrometer tables to Pernter, but it is clear from the introduction that Hann should have the credit.

in the first column being used when the "wet-bulb" reading is above the freezing-point, those in the second column when it is below :—

Strong wind	0·000656 ...	0·000579
Moderate wind	0·0008 ...	0·000706
Calm	0·0012 ...	0·001060

There is a natural tendency to regard the formulæ for strong wind, moderate wind and calm as on the same footing. It should be emphasised, however, that the strong wind formula has a firm theoretical basis, the constant being easily derived from the specific heat of air, the ratio of the densities of air and vapour and the latent heat of evaporation ; and, moreover, that the validity of this constant has been verified over a great range. The moderate wind and calm formulæ are admittedly empirical ; they are mere compromises between more or less inconsistent observations.

The several curves in Fig. 1 refer to specified dry bulb temperatures, and the dew point is given as a function of the wet bulb temperature. On Glaisher's hypothesis

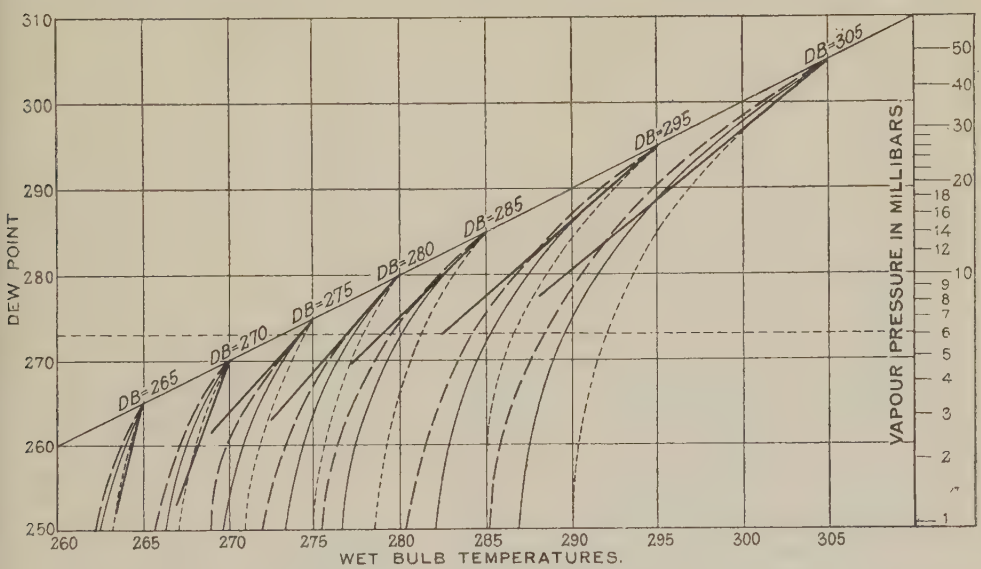

FIG. 1.—DEWPOINT AS A FUNCTION OF WET BULB READING.

For each dry bulb reading there are three graphs.
The straight line ———— gives the dewpoint by Glaisher's rule.
The highest curve — — — corresponds with the strong wind formula.
The continuous curve ——— with the moderate wind formula.
The lowest curve - - - - - - - - - with the no wind formula.

the functional relation is linear, whilst Hann's three hypotheses give three curves for each dry bulb.

The table of Hann's in which atmospheric pressure is taken as 755 mm. (1007 *mb*) has been utilised. The values of Glaisher's factor corresponding with the dry bulb temperatures in question are as follows :—

Dry bulb ...	265a	270a	275a	280a	285a	295a	305a
Factor ...	8·55	5·77	2·54	2·17	1·99	1·75	1·63

The absolute centigrade scale is in general use in the Meteorological Office for theoretical

investigations. Tables for finding humidities from observations on the absolute scale by the use of Glaisher's factors are included in the Computer's Handbook, Section I., so that the adoption of absolute temperature in the diagram is not to be regarded as an anachronism.

It will be seen from the diagram that for temperatures above the freezing point, and for air which is not too dry the Glaisher lines are in fair agreement with the run of the curves for moderate or strong winds. This agreement is such as would be expected if values of $(t-u)/(t-t_w)$ were computed from the observations and then averaged.

With large depressions of the wet bulb the Glaisher line is in each case above the strong wind curve, and there is every reason to believe that for such large depressions Glaisher's rule gives definitely false results. Thus taking the dry and wet bulb readings 305a and 290a respectively (89·6°F. and 62·6°F.), our diagram shows that according to Glaisher the vapour pressure is 10mb, whereas it cannot possibly be more than 9mb, and on the assumption of a moderate wind it is probably only 7 *mb.* The corresponding difference in the estimate of relative humidity as between 21 and 15 per cent. is serious, or at any rate would be serious if such low humidities were frequently met with in this country.

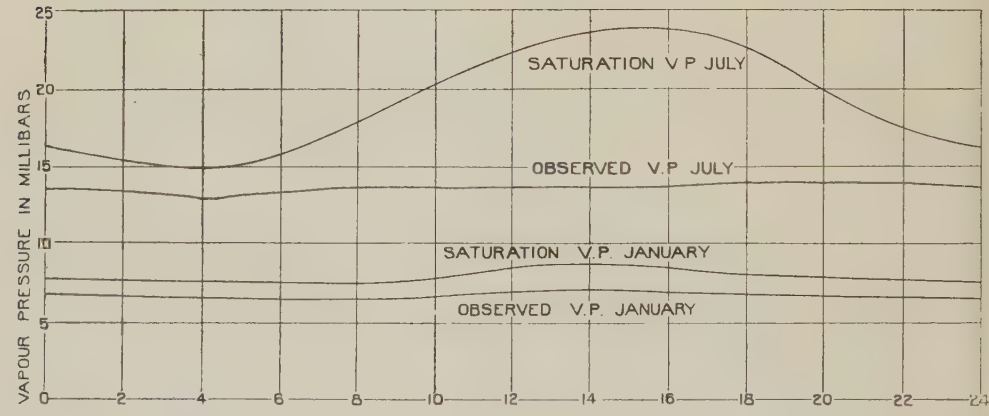

FIG. 2.—DIURNAL VARIATION OF VAPOUR PRESSURE : KEW OBSERVATORY, RICHMOND.

With wet-bulb temperatures below the freezing point the contrast between Glaisher's system and its rivals is more striking.

The calmest air occurs in frosty weather, and no doubt the Canadian observations on which Glaisher relied were taken in such circumstances ; so that the fact that for this part of the range the lines representing his formula in Fig. 1 run closely with the lines representing Hann's calm formula is satisfactory confirmation of the observations.

The change in the value of the Glaisher factor in the neighbourhood of the freezing point is very rapid. The dependence of the factor on the dry bulb temperature is obviously illogical. What matters is whether the wet bulb is ice-covered or not.

I believe that the use of Glaisher's tables should be abandoned, but my diagram brings out the great uncertainty that is involved in the use of a thermometer with unknown ventilation, by whatever system the readings may be reduced. This uncertainty is more troublesome at low temperatures than elsewhere.

It has long been realised that no system of hygrometry which depends on the readings of a wet-bulb thermometer with indeterminate ventilation can be satisfactory. In America the whirled psychrometer has been in use for many years, and it would be well if it could be introduced here. At the same time we should have forced ventilation for the thermographs from which the standard readings at the observatories are taken.

At present the uncertainty attached to the method of observation is reflected in the results. This is especially the case with regard to the diurnal variation of vapour pressure.

In Fig. 2 the diurnal variation of pressure at Kew Observatory in January and in July is compared with the variation in saturation pressure, the observations having been worked up* by Glaisher's method. The figure serves to show that Glaisher's tables are not very seriously at fault for dealing with the average conditions met with in this country ; but it also shows that a very high order of accuracy is required if the true form of the diurnal variation curve is to be determined. This high order of accuracy will not be secured unless wet-bulb thermometers with continuous forced ventilation can be installed.

As to the ordinary routine of observations, the Meteorological Office has for many years realised that much improvement in its practice is to be obtained only by the adoption of a new method of observation, and that a change from one system of computation to another to be applied to the readings of unventilated psychrometers will be only a palliative. The provision of ventilated psychrometers means, however, the substitution of a complicated procedure for a simple one at every climatological station, and is a step for which abundant justification is required. We are still wanting information as to the magnitude of the errors which are involved in the use of the unventilated psychrometer in the conditions prevailing in this country, but from investigations now in progress, some definite conclusion should be arrived at before long. In the meantime it is, I think, desirable to make general the use of the "moderate wind" formula for the unventilated psychrometer and to give up Glaisher's method of reducing the observations.

* The saturation-vapour-pressures have been taken as corresponding with the average temperatures, and the "observed" vapour-pressures have been derived from the saturation-vapour-pressures by utilising the average relative humidities. The data will be found in *Hourly Values from Autographic Records.*

THE WET AND DRY BULB HYGROMETER.

BY

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THE wet and dry bulb thermometers form the simplest instrument for ascertaining the humidity of the air, and in some form are in general use. In the autumn of 1917 I began an experimental inquiry into the reduction of their readings. There are two main conditions under which they are used, *i.e.*, in still air or in moving air. Starting with Clerk Maxwell's formula for still air ("Ency. Brit.," 9th Edition, Article Diffusion),

$$p=p_w-\frac{PS_p}{L\sigma}\left(\frac{K}{\gamma D}+\frac{AR}{4\pi CS_p\rho D}\right)(t-t_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where :—

p is the pressure of aqueous vapour in the air at a temperature t ;
p_w the maximum pressure of aqueous vapour at the temperature of the wet bulb t_w ;
P the whole pressure of the air ;
S_p the specific heat of air at constant pressure ;
L the latent heat of water at t_w ;
σ the specific gravity of aqueous vapour compared with air ;
K the thermometric conductivity of air ;
γ the ratio of the specific heats $=1{\cdot}41$;
D the diffusivity of aqueous vapours in air ;
A the area of the wet bulb ;
R the radiation constant for the wet bulb ;
C the electric capacity of the bulb ;
ρ the density of air.

I tested its validity by replacing the dry air by dry hydrogen ; and by data at reduced pressure in air. The results showed that Maxwell's formula satisfied the data obtained in such a dry still gas as that inside a porous pot soaked in strong sulphuric acid.

The more important condition, *i.e.*, in moving air, was submitted to experiment, and was discussed theoretically. One theoretical method was to take Maxwell's formula for dry air and consider how it should be modified for air in motion. As soon as the velocity is great enough the diffusion effect will be very large compared with the radiation effect ; moreover, the conduction effect would increase *pari passu* with the diffusion effect. Arguing in this way and using the results of experiment, the formula in practice reduces to

$$p=p_w-\frac{PS_p}{L\sigma}(t-t_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This view was put forward at a meeting at the Meteorological Office, and in the discussion Major G. I. Taylor outlined a theory based on the passage of heat and water-vapour through the eddy-free layer next the wet thermometer to the eddy layer beyond. In the eddy-free layer his theory leads to the formula (k=the calori-

metric conductivity and p_e the pressure of aqueous vapour at the junction of the two layers and t_e its temperature)

$$p_e = p_w - \frac{P}{L\sigma} \cdot \frac{k}{D\rho}(t_e - t_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Now, since $\frac{k}{D\rho}$ for air is nearly numerically equal to S_p the formula in effect reduces to

$$p_e = p_w \quad \frac{PS_p}{L\sigma}(t_e - t_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In the second eddy layer the formula for the exchanges is

$$p = p \quad - \frac{PS_p}{L\sigma}(t - t_e) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

When the effects of the two layers are combined we have

$$p = p_w - \frac{PS_p}{L\sigma}(t - t_w)$$

a formula the same as (2) above.

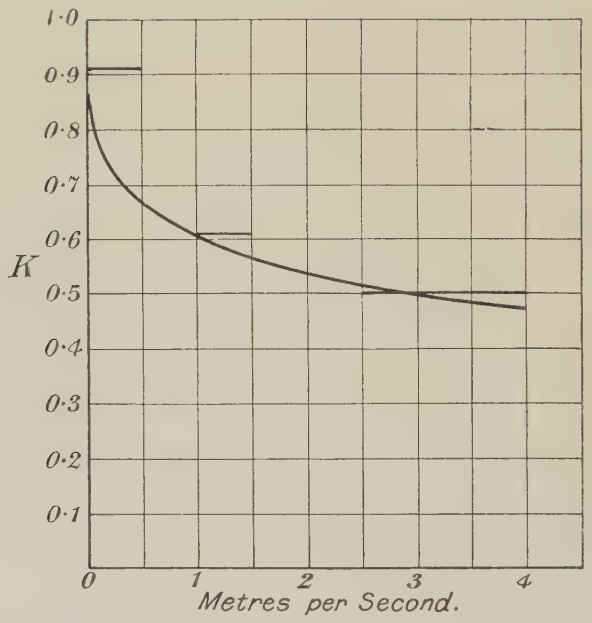
The formula was tested experimentally. A short test tube, 2·3 cm. diameter and 10 cm. long, was closed by a cork with three holes in it, through which passed an entrance glass tube leading to the bottom, an exit tube from near the top, and a thermometer graduated in 1/10ths of a degree. The wet bulb was made by wrapping one or two layers of linen gauze about the bulb of the thermometer and tying this in place with cotton thread. The wet thermometer was moistened by immersing it in a beaker of water before each experiment. To prevent heat from coming from the outside to this apparatus it was enclosed in a larger vacuum-jacketed test tube, and the intervening space was plugged with cotton wool. In some experiments this vacuum-jacket was dispensed with, for the complete experiment only lasts about four or five minutes, and not much heat can get in in that short time. The exit tube was connected to the suction nozzle of a Lennox electrical blower, so that a rapid draught could be maintained through the apparatus. The entrance tube was connected to a tall tower of pumice saturated with strong sulphuric acid in order to give a supply of dry air.

With dry air the following readings were obtained :—

Dry Air °C.	Wet Bulb °C.	Vapour Pressure at the Temp. of Wet Bulb divided by the depression of Wet Bulb.
15·15	3·1	0·477
15·1	2·8	0·472
18·2	4·7	0·460
16·7	4·0	0·474
17·9	4·7	0·483
18·2	4·9	0·476
		0·474 Mean.

The pressure in the apparatus during the passage of the air stream was determined by substituting for the thermometer a pressure gauge containing mercury. This showed that the pressure inside was 25 mm. less than atmospheric when the motor was working at its highest speed. Therefore, the theoretical constant is $735 \times 0{\cdot}2375/603 \times 0{\cdot}622$, or 0·473, which is in good agreement with the experimental result.

The velocity of the stream of air was ascertained by means of an air meter (Negretti & Zambra), fitted to the side of a box from which the air was drawn. The velocity of the air was found to be 86 feet per minute, and this multiplied by the ratio of the square of the diameter of the aperture of the air meter to the square of the diameter of the tube gave 3·92 metres per second for the velocity of the



Variation with air-speed of the coefficient K in the convection formula.

air passing over the wet bulb. Further experiments were made with hydrogen and with carbon dioxide, to which we have not space to refer, but the results were in agreement with the theory.

Some experiments were made with the same apparatus to measure the amount of aqueous vapour present in air. For this purpose the apparatus for delivering dry air was removed and the air from the room drawn in with the same velocity. At the same time observations were made with Regnault's dew-point apparatus to determine the dew-point and thus obtain the true aqueous pressure in the air.

Arising from these experiments and other data it was possible to draw a curve representing the value of the constant by which the depression of the wet thermo-

meter must be multiplied in terms of the velocity of the air up to 4 metres per second. The diagram is shown on previous page.

This refers to air pressure of 760 mm. in the formula $p=p_w-K(t-t_w)$.

The formula may be called the convection formula.

The three horizontal lines in the diagram represent Pernter's three values of the constant, *i.e.*,

0·91 for calm air velocity 0 to 0·5 m. per second.
0·61 for light winds ,, 1 to 1·5 ,, ,,
0·50 for strong winds velocity above 2·5 m. per second.

A fuller description of this method is given in the new "Dictionary of Applied Physics."

The convection formula may be applied to explain the "spheroidal" state. A drop of water in a platinum basket in the centre of a flame evaporates rapidly and its temperature will be t_w in our expression. Again, the formula illustrates the extinction of flames by a shower of falling drops. Reference was made to these applications at my lecture before the Royal Institution, April, 1921.

NOTE ON PSYCHROMETRY IN A WIND CHANNEL.

BY

R. A. Watson Watt, *F.Inst.P.*

ABSTRACT.

Experiments are described showing that the formula used in reduction of data from the ventilated psychrometer applies at air speeds of 60 to 90 miles per hour without appreciable change of constants from those appropriate to a speed of 10 miles per hour.

The experiments covered by this note were undertaken in order to test for variation, with air speeds of the order of aeroplane flying speeds, of the factor A in the ordinary formula of the ventilated psychrometer.

$$p - p_w = \frac{AP}{1000}(t - t_w)$$

where p is the required vapour pressure.

p_w is the saturated vapour pressure corresponding with the wet bulb temperature.

t and t_w are dry and wet bulb temperatures.

P is the pressure in millibars.

A is a constant for a given air speed.

The work was carried out in the 7 ft. wind channel of the Royal Aircraft establishment. Two wet and dry bulb psychrometers of the type adopted by the Meteorological Office for use in aeroplanes, were mounted on a standard type of wing strut in the centre of the channel. Psychrometer No. 1 had the bulbs 5 ft. above the floor of the channel and was held 1 ft. out from the strut. No. 2 was $3\frac{1}{2}$ ft. above floor and close up to the strut. In both cases the wet bulb was down wind.

Comparison was made with the readings of two Assmann psychrometers outside the channel, No. A 3 ft. above main chamber floor, near channel intake, No. B on a rail 2 ft. above top of channel. The results are set out in Table I.

The vapour pressure has been computed for each psychrometer using the value of the constant A which has been standardised for the Assmann psychrometer (in which the air speed is of the order of 10 miles per hour), and the means for each pair of instruments are tabulated in columns 5 and 7.

The mean difference of the computed vapour pressures for the interior and exterior of the channel is 0·8 per cent., the mean deviation without regard to sign is 1·4 per cent. The variation of computed vapour pressure with the 50 per cent. variation of air speed covered by the experiments is shown by Table II.

These results point to a regular slight decrease of A with air speed, amounting at 90 miles per hour to some 1 per cent. of the 10 miles per hour value.

This variation is, however, distinctly less than the differences of vapour pressures computed from similarly exposed psychrometers, which, as shown in Table I, cols. 6 and 8, amounted in the mean to 2·6 per cent. for the aero-psychrometers, and to 1·4 per cent. for the Assmann instruments.

The conclusion may, however, safely be drawn for the ordinary meteorological

TABLE I.—*Experimental Data and Computed Vapour Pressures.*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Experiment No.	Date.	Air speed (M.P.H.).	Temperature, °F.	Mean vapour pressure p_a from aero-psychrometers *mb*	Difference between v.ps. from aero-psychrometers Per cent.	Mean v.ps. p_s from Assmann psychrometers *mb*	Difference between v.ps. from Assmann's. Per cent.	Difference between computed vapour pressures *mb* in cols. (5) and (7).	Difference $\frac{p_s - p_a}{p_s} \times 100$ Per cent.
					+				+ —
1	22/1/20	60	58·0	9·6	2·1	9·6	...	0·0	
		70	59·2	9·75	3·1	9·7	...	—0·0 5	0·5
		80	60·3	9·8	2·0	9·8	...	0·0	
		90	62·6	9·95	5·0	10·0	+ —	+0·05	0·5
2	27/1/20	60	61·4	9·2	2·2	9·45	3·2	+0·25	2·6
		70	62·5	9·7	6·2	9·5	2·1	—0·2	2·1
		80	64·7	10·05	5·0	10·15	1·0	+0·1	1·0
		90	66·8	10·2	7·8	10·2		0·0	
3	28/1/20	60	60·0	11·0	0·0	11·45	4·4	+0·45	4·4
		70	61·8	11·35	2·6	11·45	0·9	0·1	0·8
		80	63·6	11·6	0·9	11·65	0·8	0·05	0·4
		90	65·5	11·75	3·4	11·85	0·8	+0·1	0·8
4	3/2/20	60	50·7	7·85	6·4	7·8		—0·05	0·6
		70	51·5	7·9	3·8	7·75	1·3	0·15	1·9
		80	52·9	7·9	2·5	7·85	1·3	0·05	0·6
		90	54·2	8·0	2·5	7·85	1·3	0·15	1·9
5	3/3/20	60	51·9	7·6	0·0	7·45	1·3	—0·15	2·0
		90	55·5	7·7	0·0	7·7		0·0	
6	3/3/20	60	56·3	10·95	0·9	11·65	6·0	—0·30	2·6
		70	57·4	11·5	0·0	12·3	6·5	+0·8	6·5
		80	58·6	12·0	0·8	12·65	5·5	0·65	5·1
		90	60·6	12·25	0·8	13·2	3·0	+0·95	7·2
Means					+2·6%		+1·4%		+0·8%

TABLE II.—*Percentage Difference between Computed Vapour Pressures at Four Air Speeds.*

Experiment No.	Air Speed.							
	60 M.P.H.		70 M.P.H.		80 M.P.H.		90 M.P.H.	
	+	—	+	—	+	—	+	—
1		0		0·5		0	0·5	
2	2·6			2·1	1·0			0
3	4·4		0 8		0·4		0·8	
4		0·6		1·9		0·6		1·9
5		2·0						0
6		2·6	6·5		5·1		7·2	
Sums	7·0	5·2	7·3	4·5	6·5	0·6	8·5	1·9
	+1·8		+2·8		+5·9		+6·6	
Means	+0·3%		+0·6%		+1·2%		+1·1%	

applications of psychrometry that the value of A in the psychrometric formula applies equally to air speeds of 10 and 90 miles per hour, any error due to its variation being well within the casual error of observations in wet and dry bulb psychrometry.

The range of temperature (51 to 67°F.) and vapour pressure (7·5 to 13·2 *mb*) covered by the experiment is not large ; a much fuller series of experiments had been arranged, to cover artificially produced temperatures and humidities of considerable range, but circumstances intervened which prevented the work being carried out.

It seems desirable that work on the wider range should be done, preferably by comparison of the aeroplane psychrometer with a hygrometer also placed in the wind channel.

Thanks are due to the Superintendent, Royal Aircraft Establishment, for making the wind channel available ; and to the wind channel staff for their help in the work.

This Note is published by permission of the Director, Meteorological Office, at whose instance the work was undertaken.

THE TILTING HYGROMETER: A NEW FORM OF ABSORPTION HYGROMETER.

BY

The late H. G. Mayo, *M.A., and* Professor A. M. Tyndall.

The following work arose out of a demand for a hygrometer which would be suitable for use in cold stores. While the instrument herein described fulfils this condition, it is also convenient for use at ordinary room temperature, and may appeal to some as instructive as a piece of laboratory apparatus in a university course. It should be mentioned, however, that the form that it takes was determined by the purpose for which it was designed—namely, for cold store work. For use at room temperatures only the instrument can be modified, so that it is more " foolproof."

The method employed is that of abstracting the moisture from a given sample of air with phosphorus pentoxide, and measuring the resultant change of pressure on an oil U-tube gauge.

The following advantages may be claimed for the instrument :—

(1) It is portable.

(2) It is rapid in action, a reading of the water vapour pressure in a cold store being obtainable in less than three minutes, in terms of the length of a column of oil.

(3) Tests made at temperatures ranging from —10°C. to 20°C. show that it is reasonably accurate over this range.

(4) It can be used on board ship or in any other place where a steady support is not procurable.

Its main objection as an instrument for cold stores is that it must be placed in the store sometime before use, and it is necessary for the operator to enter the store for the purpose of taking the readings.

The present form of the instrument is described below under a special heading. But the following historical summary and account of earlier forms which we have tried will serve to bring out the reasons for this particular design.

Historical Summary of Work on Absorption Hygrometers.

Edelmann (Wied. Ann., VI., p. 455, 1879) noted the reduction in pressure brought about by exposing a given volume of air to sulphuric acid, which absorbed the water vapour present.

Van Hasselt (Mbl. Nt. Amsterdam, 1879) brought about the required absorption by breaking a bulb of P_2O_5 inside the vessel. But in neither case can the instrument be regarded as suitable for repetition work in hygrometry.

Sondern and also Matern (Wied. Ann., IX., p. 147) exposed a sample of air to a water surface and measured the change in pressure (or volume) brought about by saturation.

A. N. Shaw (Trans. Royal Soc. Canada, Vol. X., 1916) on similar lines has devised a constant pressure absorption hygrometer, using sulphuric acid as the drying agent. But the influence of the glass walls of the apparatus and the presence of a number of taps, in our opinion, introduce defects into his apparatus which make it both inaccurate and unsuitable for cold store work.

Preliminary Experiments.

A theoretical calculation from the coefficient of diffusion of water vapour through air shows that in any practical form of apparatus the method of drying a sample of gas by diffusion leads to a slow rate of working. This was confirmed in an experiment in which, by means of a loosely fitting rubber bung, the upper and lower parts of an ordinary desiccator were virtually cut off from one another. The upper part contained the sample of air, and the lower some phosphorus pentoxide. It was arranged that, without opening the desiccator, the bung could be pulled up by a thread, so that there was a wide free passage opened up, through which diffusion of water vapour could take place.

It was found that ultimately the U-tube gauge connected to the desiccator became steady, indicating that the absorption was practically complete, but that at least half an hour elapsed before this occurred.

In practice, therefore, some arrangement must be adopted in which the air is passed over or through the drying agent instead of simply being left in contact with it.

Accordingly a device was tried in which the sample of air was placed in a tube joining the ends of a glass U-tube half-filled with mercury. Without going into the details of the arrangement, it may be said that it was possible to insert in this sample a rod coated with phosphorus pentoxide, and then to drive the air backwards and forwards over it simply by rocking the U-tube in its own plane.

A capillary U-tube oil gauge communicating with the sample and inserted so that its plane was perpendicular to the plane of the apparatus, responded with a rapidity which showed that the absorption of the moisture in the to-and-fro motion was effectively carried out.

But the heat generated in the P_2O_5 produced a temperature effect which, owing owing to the bad conductivity of the glass walls, died down only slowly, and so greatly decreased the rate of working the instrument.

Moreover an important point was emphasised by this design. If moist air is admitted to a perfectly dry vessel, the humidity of the sample rapidly falls due to adsorption of water vapour by the walls. When the mercury is raised this water film is covered over by or shared with the mercury surface, and not removed by the P_2O_5. In this way the mercury gradually gets wet in a sequence of experiments, and it is then impossible to fill the vessel with a true sample of the external air, because the humidity will change by contact with the walls and mercury before connection between the sample and the outside atmosphere can be cut off. This was shown by the fact that the apparatus gave good results when first set up, but gradually failed.

We believe that this effect vitiates nearly all the early experiments referred to in the historical summary above.

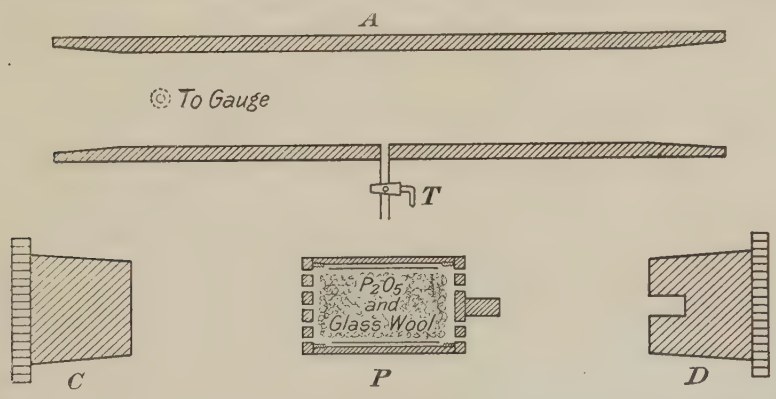
To eliminate these troubles an arrangement is necessary in which the surface area in contact with the sample is practically unchanged throughout and is made moreover of metal instead of glass to reduce both the surface effect and the temperature effect due to heating of the drying agent.

In the first instrument of this type, the air in a brass cylinder was made to surge backwards and forwards through P_2O_5 in a side tube by working a rod and piston in the cylinder. The rod passed through a stuffing box at each end, so that the volume of the vessel did not change with the motion of the piston. Taps were provided so that the cylinder could first be filled with the sample by carrying out a number of strokes without exposing the P_2O_5.

Trials in cold stores revealed troubles due to the hardening of the packing of the stuffing boxes and leakage of the various taps. Moreover, the process of ensuring before starting that the adsorbed film on the inner walls of the cylinder was really in equilibrium with the sample admitted involved a tedious number of strokes of the piston and loss of time. We believe that those difficulties are all met in the final form of apparatus—in so far as it may be said to be final.

Final Form of Apparatus.

The rod and piston is replaced by a brass plunger fit ing a brass cylinder well but sufficiently loosely to slide from one end to the other without lubrication when the cylinder is tilted through about 30°. The figure shows the details of the arrangement. In the ordinary way the cylinder *A* is left freely open at both ends so that the film on its walls is in equilibrium with the air of the room. When a measurement of humidity is required it is closed at both ends by the insertion of the plunger and two ground-in solid plugs *C* and *D*, the tap *T* being kept open during this operation. A hole in *D* receives at the end of a stroke a pin projecting from the plunger *P*. In this way the plunger may readily be inserted into and removed from



the tube before and after an experiment without touching it with the fingers. The plunger *P* is hollow and its ends perforated. It is loosely packed with glass wool dipped previously into P_2O_5 powder. No P_2O_5 is placed on the wool touching the ends of the plunger, and a glass sleeve similarly protects its sides.

Communication with the outside air is cut off by closing the tap *T* and the cylinder is then tilted so that the plunger falls towards the plug *C* ; air passes through the P_2O_5 and dries in the process. Reversing the direction of the tilt reverses the direction of motion of air. Spring clips are fixed to the end of the cylinder to hold the plugs in position and prevent them being loosened by impacts from the plunger.

A few oscillations are sufficient to dry a sample, as may be seen by the motion of the oil gauge which is connected to the cylinder by a side tube. In general, however, about twenty oscillations have been made first and these have been followed by a brief halt and a few more oscillations. In this way the greater part of the effect of evolution of vapour from the walls and of heat from the P_2O_5 is eliminated.

Very consistent results have been obtained with this apparatus both at room temperature and in cold store. Moreover, the possibility of leakage is greatly decreased owing to there being only one tap to look after and no stuffing boxes.

In calculating the humidity from the gauge reading two constants are necessary, the density of the oil and the relative volumes of the wet air in the cylinder and the dry air in the plunger. These factors, once measured, are constants for the instrument if it is made to pattern. The gauge tube is capillary so that the motion of the oil produces no appreciable change of volume in the sample.

The relative internal volumes of cylinder and plunger were measured and it was calculated from these that the observed reduction in pressure must be multiplied by 1·30* to give the true vapour pressure of the wet air before it was passed through the drying chamber. A chemical hydrometer was set up by which the mean humidity of the air over a period of half-an-hour was determined. This reading was compared with the average of a set of readings with the absorption hygrometer, taken at the beginning and end of the same period.

Two typical sets of results are given in Table I., the first obtained at room temperature in the laboratory and the second in cold store. In general six readings were taken with the absorption hygrometer, three just after the chemical hygrometer was started and three just before it was completed. It was assumed that the humidity was changing if at all at a uniform rate during this time, so that the mean reading might be compared with that of the chemical hygrometer. It will be seen that the mean absorption hygrometer reading is in excellent agreement with that of the chemical hygrometer. In fact the results practically always were in good agreement as may be seen from the summarised readings given in Table II.

The hygrometer was tested at room temperature and in several cold store chambers in the Bristol district.

Column 1 of the table gives the temperature of the air in Centigrade degrees, column 2 the difference in level in cms. (h) of the oil gauge column.

Column 3 gives the vapour pressure in mms. of mercury obtained from (h) by multiplying it by 1·30* and by the ratio of the densities of oil and mercury. Column 4 gives the corresponding numbers obtained with the chemical hygrometer.

Column 5 giving relative humidities is included mainly to show that the values are reasonable in amount. The high humidity (97 per cent.) taken at −9·5°C. was obtained by placing the instrument in the duct leading directly from the chamber containing the brine pipes to the store. That of 92 per cent. at −10°C. was obtained in a store recently filled with frozen meat.

The hygrometer therefore when compared with the chemical hygrometer stands the test and is naturally more convenient and rapid for general use.

It should, however, be pointed out that with the instrument in this form the readings are useless in an atmosphere which is rapidly changing in temperature or when the instrument has been brought into a room the temperature of which is different from that of the instrument. For such cases it would be necessary to have a dummy cylinder on the other end of the gauge—as indeed we used in some preliminary earlier experiments—in order that the temperature changes may affect both sides equally. But the simplicity and convenience of the hygrometer is thereby somewhat sacrificed and provided care is taken not to touch the cylinder with bare hands or to breathe upon it, this elaboration is unnecessary in most cases.

* The four observations marked with an asterisk in Table II. were taken with an instrument for which the constant was 1·19 instead of 1·30.

TABLE I.

Temperature.	Observations.		Calculated vapour pressure in mms. of mercury.
16·3°C.	Absorption Hygrometer—readings in cms....	12·7	
		12·7	
		12·6	
		12·3	
		12·4	
		12·5	
	Mean ...	12·5	8·9
	Chemical Hygrometer—		
	Volume of air	5 litres	
	Change in weight of drying tube ...	0·0454 gm.	8·9
—4·0°C.	Absorption Hygrometer—readings in cms....	3·9	
		3·7	
		3·7	
		3·7	
		3·6	
		3·5	
	Mean ...	3·7	2·9
	Chemical Hygrometer—		
	Volume of air	5 litres	
	Change in weight...	0·0147 gm.	2·8

TABLE II.

Temperature in degrees Centigrade.	Mean gauge reading in cms. of oil.	Vapour Pressure in mms. of Hg.		Relative Humidity.
		Absorption Hygrometer.	Chemical Hygrometer.	
*16·8	14·3	10·2	10·1	72
*16·0	12·93	9·2	9·2	68
*15·4	12·5	8·9	8·9	68·5
13·1	10·2	7·93	8·00	71
12·9	10·6	8·23	8·35	74
12·7	9·8	7·6	7·64	69
12·5	8·9	6·9	7·00	64
—2·5	4·0	3·1	3·20	83
—3·5	3·5	2·7	2·68	79
—4	3·7	2·9	2·80	88
—9·5	2·6 (mean of two readings only)	2·0	2·03	97
*—10	2·1	1·8	—	92

Lastly it may be seen that in special cases by suitable choice of reagent in the plunger the instrument might be adapted for rapid measurement of an impurity in air or another gas within certain limits of percentage of impurity.

A THERMAL HYGROMETER.

BY

PROF. A. M. TYNDALL, *D.Sc.*, *and* PROF. A. P. CHATTOCK, *D.Sc.*

THE primary object of the present experiments was the measurement of the humidity in the egg space under sitting hens, which was required in some work on the physics of hen incubation carried out by one of us (A. P. C.) for the Board of Agriculture.* The results obtained are, however, of more general applicability, and are here described as such.

This instrument is a development of experiments made by Orme Masson (Proc. Roy. Soc., Vols. LXXIV., LXXVIII.) and anticipated by Clayton Beadle (Nature, Vol. XLIX., p. 457; Chem. News, Vol. LXXI., p. 1; Ibid., Vol. LXXIII., p. 180).

The principle of the method is this. Very dry cotton wool exposed to damp air absorbs moisture and warms as a consequence.

The temperature rises rapidly at first; reaches a maximum; and then tails slowly off, until if the temperature of the surroundings is constant, it approaches its original value.

Using about a gramme of wool tied round the bulb of a thermometer, Masson found that the maximum temperature was reached about half an hour after the exposure of the wool to the moist air, but the approach of the temperature to its old value lasted many hours. He obtained an empirical equation to the temperature-time curve and deduced from it that if φ is the maximum temperature attained by the wool and τ the time it takes to acquire it, then φ/τ is directly proportional to the vapour pressure of the air to which it is exposed. He further suggested that this effect might be made use of for hygrometric measurements. The following work was undertaken with a view to obtaining on these lines a practical form of hygrometer suitable either for general work or more particularly for work in confined spaces.

If the temperature of the surroundings varies, the indications of the thermometer will, of course, also vary and the connection between temperature and humidity will be upset.

Masson put his apparatus in a water jacket kept at constant temperature by a thermostat, but this is only feasible under special conditions. It was therefore important to reduce the direct effect of temperature relatively to that of the moisture as much as possible, and one way of doing so was to shorten the period of changing temperature that follows the exposure of the wool.

This we did by using in place of the thermometer a thermo-electric junction of very thin constantan and copper wires, and tying upon it about a centigramme (instead of a gramme) of cotton wool; the result being that when the wires were connected to a dead-beat galvanometer and the wool exposed to damp air after drying, the maximum deflection was reached in about 10 seconds after exposure instead of half an hour. One result of this reduction of the time of exposure is that the total amount of water vapour extracted from the air is relatively very small, an important point when one is requiring the humidity of a small confined space.

It is this maximum deflection that we have used as the measure of humidity.

* The complete hygrometric results obtained in this work will be included in a Paper on the "Physics of Incubation" now in the course of preparation. (A. P. C.)

We have used throughout this work a Cambridge Paul Ayrton Mather dead-beat galvanometer of low resistance. In ordinary air of average humidity the deflections were of the order of 20 to 30 cms. In all that follows a resistance of 25 ohms was placed in series with the galvanometer to reduce its sensitivity somewhat. The rises in temperature of the wool which took place were of the order of one-tenth to one degree.

Experiments seemed to indicate that over a wide range of humidity this maximum deflection was directly proportional to the pressure of the water vapour in the air sample provided that other conditions such as temperature, physical state of the cotton surface and geometry of the instrument remained unaltered. That is, at any rate, the conclusion that one would draw from the following results.

The details of the method of exposing the wool to a sample of air of known humidity need not be given here, because the apparatus used in obtaining these results was determined by the circumstances of the main investigation, namely, the measurement of humidity in incubators and under hens. Suffice it to say that a sample of air from a hen incubator, of humidity determined by the chemical hygrometer, was obtained in a small bottle the mouth of which was closed by waxed paper. The thermocouple with its two junctions, one covered with wool and the other bare, was enclosed in a glass tube with a pointed end and a hole in its side opposite the wool. The wool was tied on tightly to the junction in five or six places with sewing-silk; the two junctions were arranged to be fairly close together so that any disturbances other than that set up by absorption of water vapour might affect both equally. It was arranged that the tube could be transferred from a dry atmosphere to the bottle by piercing the waxed paper with the sharp point of the tube, the tear in the paper being sealed immediately afterwards with a rubber pad.

Table I. gives the results obtained, with the time in minutes added during which the cotton wool had been drying, since it was last exposed to moist air.

TABLE I.

Time in minutes of drying of cotton wool.	Grammes of water vapour in 1 litre of incubator air (M).	Maximum galvanometer reading (G).	G/M.
All night.	0·0200*	5·50	275
38	0·0210	5·92	282
20	0·0211	6·22	295
31	0·0211	6·05	286
29	0·0217	6·15	284
15	0·0205*	6·22	303
15	0·0201*	6·18	308
104	0·0202	6·05	299
48	0·0162*	4·98	307
31	0·0142	4·05	285
31	0·0136	4·00	294
30	0·0134	3·73	279
27	0·0132	3·73	282
86	0·0100	2·76	276
49	0·0105	3·10	295

The temperature of the wool was throughout 40°C., the same as that of the incubator.

The figures in the last column of the table show that the galvanometer readings are reasonably proportional to the corresponding vapour pressures in the incubator. Of the four readings that are badly out (shown with asterisks), two were for wool that had only been dried for 15 minutes, one was for wool that had been drying all night; for the fourth no reason is known for the discrepancy.

Measurements of the time taken by the galvanometer in attaining its maximum deflection show no appreciable variation over the range of humidity used, though its value, 11 seconds, was not large enough to be certain to nearer than 2 or 3 per cent. Under these circumstances proportionality between vapour pressure and maximum deflection is consistent with Masson's results.

The test was sufficient for the purpose in hand when it was made. Later work, however, showed that readings of the temperature rise of cotton wool in air of a given humidity vary from day to day, although the physical conditions appear

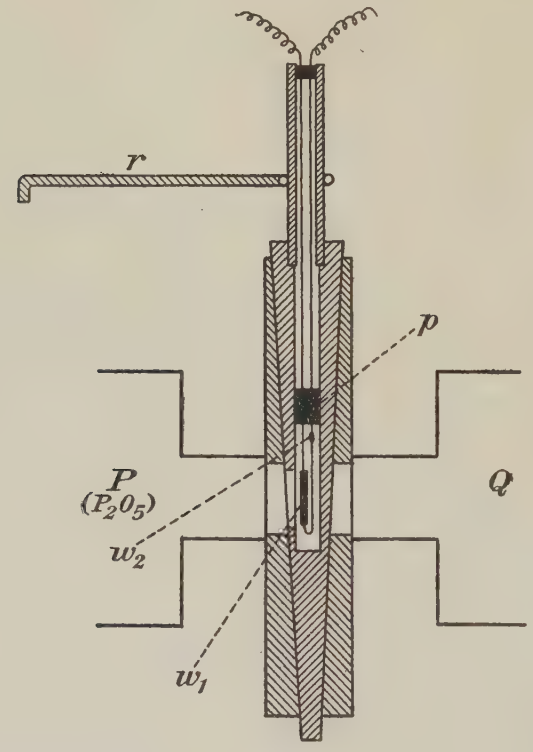


FIG. 1.

to be constant. This suggests that similar variations might have been occurring during these readings and that the straight line relationship was, therefore, possibly spurious. However, it was these results that led us to convert the instrument into one of more convenient form which may be termed the "Rotor" form.

In the rotor form the chamber containing the moist air is permanently attached to the tube containing the cotton wool, and it is by rotation of this tube about its axis instead of an end-long motion that the cotton wool is exposed.

Fig. 1 shows a section through the hygrometer as first set up. The centre portion is the rotor. It consists of two brass tubes ground to fit one another with a slight taper. The inner tube contains the junctions w_1 covered with cotton wool and w_2 bare, and is pierced by a single hole opposite the latter. The outer tube is pierced by two holes opening respectively into the two metal chambers *P* and *Q*. "*p*" is a sealing-wax plug and "*r*" an arm for rotating the inner tube.

In chamber *P* a tray of P_2O_5 is placed. Chamber *Q* is either open to the air or contains a solution, the vapour pressure of which is required.

As shown in Fig. 1, the wool is exposed to *P*. It is therefore drying. A half turn of the inner *R* tube will expose it to the moist air of *Q*.

The procedure was to turn the rotor, note the maximum galvanometer reading, and then turn the rotor back again so that it was left to dry for about half-an-hour before obtaining another galvanometer reading.

We hoped that when the cotton wool had had time to settle down its power of absorbing moisture would become constant, and an occasional single standardisation of the rotor hygrometer with air of known humidity would be sufficient.

This, however, is not the case. The wool reaches a condition of average constancy, but fluctuates up and down. In illustration of this we give in Table II. the record of a certain rotor which has been most frequently standardised. Neglecting the very low value of the constant (deflection per mm. pressure) that followed a rest of more than 7 weeks, there are fluctuations of about 8 per cent. above and below the mean value of the constant during the weeks the instrument was in use.

TABLE II.

Date.	Pressure of water vapour in mm. by drying tube (A).	Mean rotor reading in cm. (G).	Temperature of rotor Centigrade.	Constant. G/A.
Aug. 23 ...	13·2	8·09	22·3	0·613
„ 24 ...	11·2	6·47	19·9	0·578
„ 24 ...	16·9	10·26	26·0	0·605
„ 24 ...	15·2	9·74	24·0	0·641
„ 27 ...	20·1	12·00	23·9	0·595
„ 29 ...	16·2	9·74	25·0	0·602
Sept. 1 ...	14·9	9·04	25·1	0·605
„ 1 ...	14·7	8·10	24·8	0·552
„ 4 ...	14·8	8·64	25·4	0·581
„ 4 ...	14·8	8·21	25·3	0·556
„ 9 ...	13·5	7·64	25·1	0·569
„ 9 ...	13·1	7·48	25·3	0·572
„ 12 ...	13·9	8·77	24·4	0·630
„ 12 ...	13·1	7·79	24·4	0·595
„ 24 ...	12·0	6·83	25·1	0·572
„ 24 ...	11·2	6·32	25·3	0·565
„ 25 ...	13·3	7·63	23·9	0·575
	Rotor	not being used, wool	drying.	
Nov. 2 ...	10·5	7·13	22·4	0·680
„ 2 ...	10·1	6·58	22·2	0·650
„ 4 ...	9·65	5·73	20·1	0·595
„ 4 ...	9·25	5·94	19·8	0·646

We have not yet been able to trace these fluctuations to any certain cause; but we feel sure that they are inherent in the method as it is dependent upon the

rate of absorption of water vapour by a minute lump of material of complex surface, a phenomenon which is influenced by many factors.

Attempts have been made to find a substitute for cotton wool which, by presenting a more homogeneous surface might act more consistently. Of these cigarette paper was sufficiently sensitive and probably more reliable, if used in the following way.

The fact that both with wool and paper the galvanometer deflection is apparently too small after a long period of drying (for example, the point marked with a cross in the cotton wool curve) suggested that the fluctuations might be due to some inhibiting influence delaying the start of the condensation on a very dry surface. Readings were, therefore, taken of the reverse phenomenon, namely, the cooling of the wool when the rotor was turned from the damp atmosphere to the P_2O_5 chamber.

It was shown that the actual deflection obtained was greater on turning from wet to dry than it was on turning from dry to wet. A typical set of results is given for cigarette paper in Table III., the readings being taken alternately with 10-minute intervals. Actually two hygrometers were used, one for each process. Previous calibration under the same conditions (dry to damp) showed that their constants were sensibly the same.

TABLE III.—*Cigarette Paper.*

Maximum Galvanometer Deflection.	
Dry to damp.	Damp to dry.
(3·99)	5·58
4·07	5·55
4·07	5·56
4·10	5·59
4·13	5·59
4·18	5·60
4·18	5·58
4·13	5·60
4·18	...
4·13 Mean. (Omitting 1st reading.)	5·58 Mean.

$$\frac{\text{Mean damp to dry}}{\text{Mean dry to damp}} = \frac{5{\cdot}58}{4{\cdot}13} = 1{\cdot}35.$$

It will be seen that when the rotor is turned from wet to dry, not only is the reading increased 1·35 times, but the variations are certainly less marked. This indicates that when it is possible this is the best way to use the instrument. But some fluctuations in constant did take place from week to week, as may be seen in Table IV.

To what extent the temperature of the surface affects the readings we have no definite information, but in any case the necessity for continual recalibration prevents the instrument from being of practical utility in this particular form except, perhaps, in special cases such as the one for which it was originally designed.

But one point is clearly brought out. Though the fluctuations are marked from day to day, readings taken in rapid succession are extraordinarily consistent with

one another, as may be seen from Table III. (damp to dry), taken in ordinary laboratory air on a day when atmospheric conditions were apparently constant.

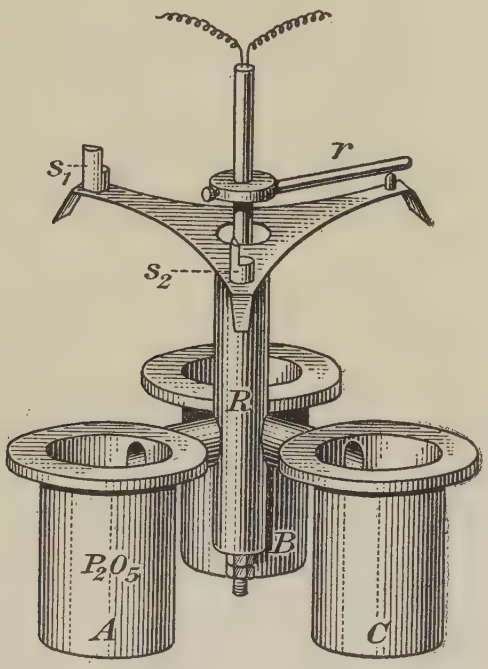


FIG. 2.

TABLE IV.—*Paper Hygrometer (Damp to Dry).*

Date.	Temperature of room, in C°.	Change of weight, chemical hygr. C.	Galv. deflection. Paper hygr. P.	P/C.
1920.				
Sept. 9 ...	16·9	0·0252	5·39	214
,, 10 ...	15·5	0·0211	4·52	214
,, 10 ...	15·9	0·0203	4·33	213
,, 12 ...	15·9	0·0228	4·65	204
,, 12 ...	16·2	0·0234	4·65	199
,, 30 ...	14·7	0·0248	5·37	217
Oct. 6 ...	15·3	0·0272	5·91	217
,, 17 ...	15·2	0·0270	5·70	213
,, 23 ...	16·1	0·0222	4·65	212
Nov. 9 ...	16·8	0·0202	3·92	194
,, 10 ...	15·1	0·0179	3·69	206
Dec. 6 ...	13·9	0·0140	2·50	181

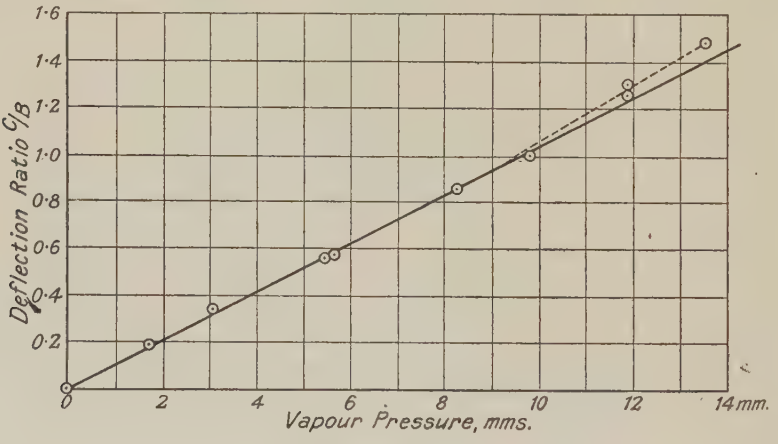
Recently, therefore, we have taken the subject up again and converted the instrument into a comparative one by the addition of a third chamber containing a liquid of known vapour pressure, as shown in Fig. 2. "*A*" contains P_2O_5, "*B*"

a solution of sulphuric acid of known vapour pressure (s)* and "C" air the humidity of which is required. The rotor R normally open to A is exposed by rotating the arm r first to B and then, after a short drying period, to C. The ratio of the two readings obtained gives the vapour pressure in terms of a standard; s_1 and s_2 are stops to ensure as far as possible identity in the degree of exposure in the two cases.

In general the constant of the cigarette paper will not change appreciably in this short time, but in practice one naturally completes the series by repeating the B reading and using the mean between them.

A thin strip of paper was used, about 0·3 sq. cm. in area and about 0·5 milligrams weight. It was twisted fairly tightly round the junction and bound to it by a strand of thin copper wire taken from a piece of lighting flex.

Table V. gives some typical results. In experiment 1 the glass lids of B and C were removed so that the two vessels were both open to the same atmosphere. The equality of the two deflections to within 1 per cent. shows that the geometry of the apparatus was nicely adjusted and the readings, therefore, independent of the



CURVE I.

direction of turning. In the second, third and fourth the vessel B contained an inner glass vessel with a mixture of one part sulphuric acid and four parts water (vapour pressure at 16°=9·9 mm.); the contents of C were varied. The last two vertical columns show the comparison of the ratio of the two deflections with the ratio of the vapour pressures of the two solutions obtained from tables.

These and other results are summarised in Curve I., the mixture in C being varied from pure acid to pure water. It will be seen that except near saturation the proportionality between maximum deflection and vapour pressure is quite satisfactory.

It is true that when two solutions of very unequal vapour pressures are compared the agreement with the value from tables might be better. But if the instrument were being used to determine a given vapour pressure one would naturally use, if possible, a standard vapour pressure in B of the same order of magnitude as the

* Ordinary pure sulphuric acid does not appear to be the best standard solution to use, as the sensitivity of paper exposed to it decreases with time. Orme Masson observed the same phenomenon and traced it to the action of oxides of nitrogen. Carefully purified acid did not give rise to it.

unknown and not widely different. An illustration of its use in this way is shown in experiment 5 in the Table, in which an acid solution of one part to 11 parts is compared with one of one part to seven parts. The agreement is there good.

TABLE V.

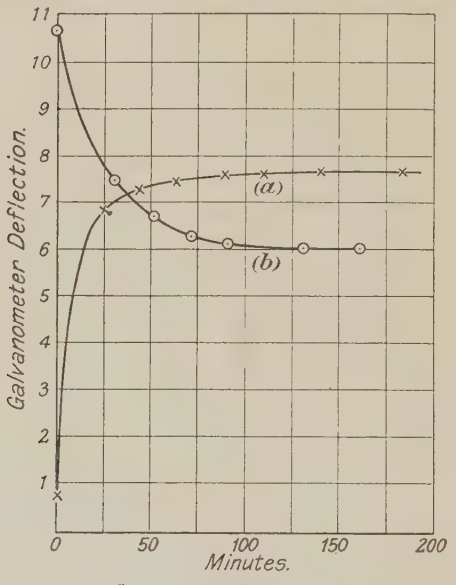
Experiment.	Temperature.	Galvanometer deflections.		Mean C/B.	X/S calculated from tables.
		B.	C.		
1.	12·5°	3·70 3·73 3·70 3·60 (3·68)	3·70 3·62 3·67 3·60 3·65	0·992	1·000
	12·7°		(3·65)		
2.	16·8°	7·55 7·52 7·42 7·54	4·17 4·17 4·17	0·556	0·56
	16·8°	7·51	(4·17)		
3.	15·2°	6·44 6·51 6·56 6·57	1·20 1·20 1·22	0·185	0·17
	15·5°	(6·52)	(1·21)		
4.	12·5°	5·83 5·90	1·95 2·03 2·02	0·341	0·32
	12·6°	(5·87)	(2·00)		
5.	16·2°	11·64 11·60 (11·62)	10·80 11·02 10·90	0·940	0·93
	16·3°		(10·91)		

For accurate work up to saturation a calibration curve is necessary unless the standard and unknown vapour pressures are nearly equal. But the linear relationship holds up to a value of humidity at least equal to those usually obtaining in ordinary air.

In our opinion, therefore, the instrument in this form is suitable for hygrometric work of various kinds and also for the purpose of measuring fairly rapidly and accurately the vapour pressures of solutions of salts or mixed salts.

A warning note should, however, be given. It is useless to take a reading soon after the vessel containing a solution to be tested has been inserted in the chamber *B* or *C*. In our case the volume of air above the liquid was about 75 c.c., and its area of cross-section 20 sq. cm. and yet it was about 100 minutes before the vapour pressure, as indicated by the deflection attained its equilibrium value.

Two cases are shown in Curve 2 (*a* and *b*); one (*a*) a series of measurements taken every 20 minutes after placing in *C* acid solution (one part to seven parts water), *C* being previously filled with P_2O_5; and the other (*b*) after inserting acid solution one part to three parts in place of water. The deflection-time curves show how with both the liquid surface and the air above it quiescent the vapour pressures



CURVE II.—(*a*) *and* (*b*).

only gradually attain their equilibrium value. Unless some means of agitating the contents is adopted this limits the rate at which the vapour pressures of a series of solutions could be examined. Even then in the case of a solution of very low vapour pressure, following one of high, a small change was observed for some hours afterwards. Presumably this was due to slow evolution of vapour from the walls of the metal and the glass.

GENERAL DISCUSSION.

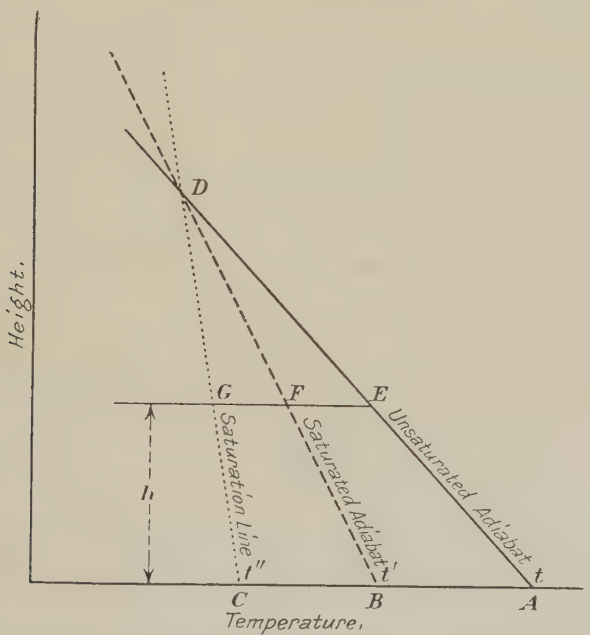
Sir NAPIER SHAW: I find myself in a position of some difficulty in opening this discussion, partly because preceding speakers have viewed the matter mainly from the point of view of the physical laboratory, and partly because the method which seems to me best suited to conditions below freezing point is apparently the one method which has not been tried—I refer to that of the self-recording hair hygrometer. After dealing with the question of hygrometers many years ago at the request of the Meteorological Council, I found that the real need, so far as meteorology was concerned, was for an instrument which should give reasonably reliable results when read by observers, not necessarily highly skilled, scattered throughout the country. Intricate questions of physics relating to sources of small errors are interesting and attractive, but of comparatively little practical importance. Hygrometry is a subject with which meteorologists concern themselves less than is generally supposed, and as hitherto treated it has been really of less service to their science than to certain of the industries. Whenever the study of humidity becomes a vital part of meteorological study the question of instrumental equipment will not present much difficulty. The slide shown illustrates the difference in point of view to which I wish to call your attention. It is a map showing the normal dew-point in July

obtained by measurements of humidity by different people all over the Northern hemisphere. The values range from 300 deg. in the Arabian Sea to 275 deg. in Greenland. The question which I wish to put is, supposing that the lines shown on the map are thought to be unreliable for their purpose, which of all the instruments described this evening should be put into the hands of the scattered observers? The temperatures shown do not go below freezing-point, and a real difficulty arises when low temperatures have to be recorded. In this country such temperatures are of comparatively rare occurrence, and we make no adequate provision for them, but in such countries as Norway and Russia they are frequent, and it is the hair hygrometer that is used.

In the study of the upper air, also, very low temperatures occur, and the only instrument used has been the hair hygrometer, I think justly, because the wet-and-dry-bulb hygrometer fails altogether in the circumstances. The recording hair hygrometer seems to be specially convenient also for such conditions as those which obtain in a cold store, because there is not much variation of temperature and observations can be taken through a window more readily than with other types of instrument. I hope I have said enough to indicate that the important matter, from my point of view, is the practical utility of the instrument in service conditions rather than its scientific precision in conditions which are appropriate to a well-equipped laboratory.

Dr. G. C. Simpson said that as Sir Napier Shaw had dealt so fully and so well with the meteorological aspect of the case, it was unnecessary for him to say more on that subject, beyond remarking that he agreed with all that Sir Napier had said.

His own contribution to the discussion would be to describe work which had recently been



done by Dr. C. W. B. Normand, of the Indian Meteorological Department, as this gave an entirely new importance to wet-bulb temperatures. Dr. Normand considers a mass of air brought into contact with a wet-bulb thermometer. Its temperature is reduced and its humidity increased, but as the bulb maintains a constant temperature there is no transfer of heat; thus the process is adiabatic. With this as a starting point, thermodynamic reasoning is applied and a most important series of conclusions reached. The following are amongst the most important.

(*a*) If t, t', t'' are simultaneous dry-bulb, wet-bulb, and dew-point temperatures respectively, then on a Neuhoff diagram the unsaturated adiabat through t, the saturation adiabat through t', and the dew-point curve through t'' all meet in a point (*D*, Fig. 1).

(*b*) As a mass of air rises adiabatically in the atmosphere its temperature follows an unsaturated adiabat, while the variations of its wet-bulb and dew-point temperature are such that they follow simultaneously a saturation adiabatic curve and a dew-point curve respectively (*F* and *G*, Fig. 1).

(*c*) The wet-bulb potential temperature is an invariant in all adiabatic changes.

(*d*) The wet-bulb potential temperature is a measure of the entropy of atmospheric air.

(*e*) When portions of air at different temperatures, but having the same wet-bulb temperature, are mixed together, the mixture has that wet-bulb temperature.

Dr. Normand also shows how the Neuhoff diagram may be used as a humidity diagram, without any assumptions involving the use of the equations on which psychrometric tables are based.

This work gives an entirely new importance to the physical meaning of the wet-bulb temperature, which is no longer to be considered simply as an interesting instrumental condition from which the humidity of the air can be determined, but, rather, that the wet-bulb temperature represents a definite thermodynamic condition depending on the entropy of the air.

Dr. Normand's Paper is at present in course of publication in the Indian Meteorological Memoirs, and should be available in this country early next year.

Mr. R. Corless: It has already been pointed out that, for meteorological purposes, the only available instruments for the measurement of humidity were the unventilated psychrometer and the hair hygrometer; and that, in the past, little use has been made of humidity observations. A new situation has recently arisen, however, for it was found that observations of humidity made on aeroplanes are of practical utility in weather forecasting, and as temperatures below the freezing-point are relatively frequent in the upper air, it has become important to find a hair hygrometer which can be used under those conditions. Interest in the properties of hair has accordingly been revived, and in view of Dr. Griffiths' remark that no important contribution on hair hygrometry has been made since the time of Regnault, it seems worth while to refer to a Paper published 20 years ago by J. Pircher (Uber den Haarhygrometer: Denkschriften d. k. Akad. d. wiss. Wien., Vol. 73, 1901), which contains a systematic comparison of the hair hygrometer under working conditions with the condensation hygrometer, and the ventilated and unventilated psychrometers. The principal results in this Paper are:—

The coefficient of elasticity of hair is 0·0027, which is greater than its temperature coefficient, and is comparable with its extension coefficient for a 10 per cent. change of relative humidity; hence it is very desirable to keep the load upon the hair constant at all relative humidities. This is not the case in the Richard hygrograph.

Hair hygrometers of the same form, when exposed to the same conditions of humidity, differ from one another by less than 2 per cent.; while the differences of relative humidity indicated by two different kinds of hair hygrometer are less than 5 or 6 per cent.

A hair hygrometer when kept for some days in a closed room at a constant relative humidity gradually reads too high by 4 or 5 per cent.; such a drift of index error does not occur if the instrument is exposed outside to the natural changes of relative humidity in the free air.

The indications of the hair hygrometer are independent of temperature, and differ by not more than 4 or 5 per cent. from the true relative humidity as indicated by Alluard's dew-point hygrometer or the Assmann psychrometer. They are nearly independent of wind velocity.

The sensitivity or the speed with which the instrument adjusts itself to a different value of the relative humidity is greater for the hair hygrometer than for the psychrometer.

In these instruments it is, of course, assumed that both the zero error and the error of scale value of the hair hygrometers used have been reduced to zero or nearly zero.

Mr. W. J. Hall: The question of humidity is of considerable importance in the textile industries. Its commercial aspect may be illustrated by the fact, for instance, that, on the Bradford system, a spinner sells worsted yarn in "18¼ per cent. condition," *i.e.*, the moisture content is 18¼ per cent. of the dry weight of the wool. Obviously with a yarn selling at several shillings per pound, the spinner will be careful not to sell wool instead of water. In certain stages of the manufacture—drawing and spinning by the Continental method for example—it is necessary to humidify the mill artificially. It is true that the limits are fairly wide; but humidification is necessary in order to work the material satisfactorily. If the wool is too dry it becomes strongly electrified during such operations as spinning. The short fibres are then thrown off from the yarn. This causes the yarn to be uneven as well as increasing the "fly waste." In rooms artificially humidified the minimum bulb difference allowed by the Board of Trade is 2°F. It is interesting

to observe in a spinning mill the increase in the number of ends breaking down as the day advances, and the atmosphere gets drier.

As regards laboratory work, we have turned to this question only during the last few weeks. We have been using an Assmann Psychrometer, and we find that it is in error by as much as 6 per cent. when compared with the chemical hygrometer. Since reading Dr. Griffiths' Paper we have decided that this is due to insufficient ventilation, for our instrument could not possibly give the necessary minimum air velocity of 3 metres per second. We hope that when this defect is remedied that the instrument will be most valuable, for none will deny its convenience. The chemical method, though perfectly accurate, is tedious and inconvenient for general use.

A suggestion has been made, and is at present under test, to use as a hygrometer a piece of cloth freely exposed to the air. The moisture content of worsted in equilibrium with a moist atmosphere has been investigated by Hartshorne. Preliminary experiments indicate that the lag is rather large. Loose wool might work better, as one would expect it to respond more quickly to changes in humidity than a piece of cloth in which the fibres are twisted together.

In any research in which textile materials are used it is important to investigate and record carefully their history. Otherwise the value of the work might be greatly diminished. As an example the late Prof. Trouton's work on flannel might be mentioned. The term "flannel" covers a range of materials; flannel may be pure wool, or it may be a mixture of cotton and wool. The results of such experiments must be applied with considerable caution. I am sure that the Director of Research at the British Research Association for the Woollen and Worsted Industries would be only too willing to assist any investigator using textile materials in research work to get samples of known history. Another point to be borne in mind is that woollen materials usually contain about 0·4 per cent. of soap when they leave the mills. This is difficult to remove by water alone. The material can be freed from soap by continued extraction with ether and alcohol.

I should like to ask Dr. Griffiths if he has observed any secular change in the hygroscopic properties of the materials he has used in his researches. Observations taken at the Bradford Conditioning House show that wool kept under test for two years has a distinctly smaller hygroscopic capacity during the second year than it has during the first year.

Dr. J. S. Anderson: Some years ago, Giraud* suggested that the hygroscopic property of glycerine, combined with the fact that the refractive index of glycerine-water mixtures varied with concentration over a comparatively wide range, might be utilised in determining the relative humidity of the air. The method he employed consisted in placing a piece of cigarette paper, initially soaked with glycerine, on the exposed face of the upper prism of an Abbé refractometer, and measuring the refractive index of the glycerine-water mixture as its concentration changed with varying degrees of humidity. For a temperature of 20°C. Giraud developed the formula—

$$H = 100(1 - a^x),$$

where H = relative humidity

$$a = \frac{n - 1{\cdot}333}{1{\cdot}4747 - 1{\cdot}333}$$

$$x = n^{2{\cdot}666}$$

and n = refractive index of mixture, 1·4747 and 1·333 being taken as the refractive indices of glycerine and water at 20°C. respectively. From this formula he calculated tables giving the humidity in terms of the measured refractive index. He also gave the temperature coefficients of refractive index for different ranges of concentration, in order to enable the relative humidity at other temperatures to be calculated. In measurements which he made with this method he obtained for the relative humidity the values 62·89 and 94·20, where the correct values were 63·17 and 94·36 respectively; no mention is made of what the comparison method was.

Now it seems to me that, although the accuracy which Giraud obtained compares very favourably with that attainable by some of the better known methods, the refractometric method could be made more accurate and more sensitive. For this it would be necessary in the first place to investigate more thoroughly than he appears to have done the equilibrium vapour pressures and the refractive indices of glycerine-water mixtures over a considerable range of temperature. If this were done with the accuracy attainable by sensitive methods which are

* F. Giraud, Journ. de Phys., 5th Ser., 3 (1913), 900.

now available, I think that the reliability of humidity measurements carried out by this method could be made at least to equal that obtained by any other method.

It is, however, with the sensitivity of the method that I wish to deal at present. Even if the laws connecting the relative humidity with variation of index of the resulting glycerine-water mixture are not accurately known, the method, owing to its "openness of scale," is a very sensitive one as it stands, and should prove of considerable use in detecting small variations of humidity or for assisting in the control of constant humidity, especially in cases where the temperature does not vary over a wide range. Its utility would, of course, be greatly widened whenever the above mentioned laws were accurately determined.

As the Abbé refractometer is designed to measure refractive indices from about 1·3 to 1·7, it is necessary to employ for the standard prism a glass having a high refractive index. Thus in one particular instrument $\mu_D = 1{\cdot}7336$. Now it occurred to me recently, while repeating some experiments which I carried out last year in connection with differential methods of refractometry,* that Giraud's method of measuring humidity could be made more sensitive by using a hollow prism containing pure glycerine instead of a high index glass prism. It would, of course, require to be sealed up in order to prevent any changes in the index of the glycerine other than those due to temperature fluctuations. In cases where the method is applied to a small range of relative humidity it would be possible to increase the sensitivity still further by filling the prism with a glycerine-water mixture having a refractive index just greater than that which corresponds to the lowest degree of humidity in the range.

In order to show the advantage of using such a modification of Giraud's method, I have calculated the angles of emergence corresponding to relative humidities of from 40 to 100 per cent. at 20°C. for different standard refractive indices and for prism angles of 60 deg. and 90 deg. The former angle is that used in the Abbé refractometer, while the 90-deg. angle cell is the arrangement suggested by Hallwachs† for measuring small differences in refractive index. We can get a rough idea of the relative sensitivity if we assume that we can with the instrument detect a difference in refractive index of one unit in the fourth decimal place.‡ This corresponds approximately to a difference in angle of 0·6′. Thus, with Giraud's method one could detect a difference in relative humidity of from about 1/9 to 1/50 per cent., according to the portion of the range under consideration, whereas, if the glass prism were replaced by a hollow prism containing glycerine, the detectable difference would vary from about 1/30 to 1/80 per cent. By restricting the range in special cases, as suggested above, the detectable difference may be made even less than 1/100 per cent.

A further advantage in the suggested modification of Giraud's method is to be found in the fact that the dispersion effects are considerably reduced, since the dispersion of the glycerine-water mixture will not differ very greatly from that of pure glycerine, except perhaps at high humidity values. Thus it would probably be found unnecessary to use a compensating device as in the Abbé refractometer.

In a similar way temperature effects would be reduced, as the temperature coefficient of the mixture will not differ greatly from that of glycerine, except again when one is dealing with high values of humidity. It should be borne in mind, however, that in cases where the temperature is varying rapidly the comparatively large volume of glycerine in the prism would not attain the appropriate steady state so rapidly as the film of the glycerine-water mixture. In such cases it might be advisable to use a fluor crown§ glass prism as the standard, thereby sacrificing the advantages of similar dispersions and temperature coefficients, but at the same time retaining the advantages accruing from the use of a lower refractive index.

With regard to the relative advantages of the 60 deg. and 90 deg. cells there is very little to choose so far as sensitivity is concerned. The former has the advantage that the refractive index of the standard can be measured directly by removing the cigarette paper and determining the critical angle of emergence. On the other hand, the latter is probably easier to make accur-

* *See* J. S. Anderson, Trans. Opt. Soc., 22 (1920-21), 156.

† W. Hallwachs, Wied. Ann., 50 (1893), 577 ; *see* J. S. Anderson, *loc. cit.*

‡ A good instrument will yield this degree of accuracy, but it is a little doubtful whether one can get a sharp enough edge to set on when using the cigarette paper method, owing to difficulties connected with the illumination. The sensitivity may, therefore, not be quite so great as the deduced values would indicate.

§ It is possible to obtain a fluor crown glass with approximately the same refractive index as that of pure glycerine.

ately, and it has the further advantage that the calculations involved are somewhat simpler. For some purposes it might be convenient to use a cell having angles 30 deg., 60 deg. and 90 deg. and to make suitable arrangements for utilising either the 60 deg. or the 90 deg. angle.

There are one or two other modifications of Giraud's method which might be found of some use, especially where a high degree of accuracy is not required. For example, instead of setting on the line of division between dark and light portions of the field of view in the observing telescope, it would be possible to use a microscope focussed through the angle of the cell on a portion of the cigarette paper, preferably on an edge.* The microscope could then be rotated about an axis approximately passing through the apparent position of the edge, until the image just disappeared. This position of the microscope would then correspond to the critical angle of emergence. In order to obtain a sharp disappearance of the image it would be necessary to reduce the aperture of the microscope. I have tested this method of observation in a rough way and it seems to show some promise of success. Quite a good approximate setting can even be made without a microscope at all, by observing through two small pin-holes or narrow slits fixed to the two ends of a piece of tubing. Any transverse motion of the image in the field of view, as the angle is altered, could be compensated by introducing a plane parallel piece of glass in the path of the beam and rotating it until the image is brought back to the centre of the field. Such a compensation would not affect the value of the measured angle of emergence, provided the piece of glass is of good quality and has accurately plane parallel sides.

The suggestions which I have briefly outlined may be of some assistance to those who wish to investigate the method more fully. Some of the points dealt with will probably enable those who find the ordinary Abbé refractometer an expensive piece of apparatus to try some of the modifications which involve the use of simpler apparatus already at their disposal.

In the portable form of dew-point apparatus (Fig. 9), described by Dr. Griffiths, there is one minor defect which could easily be remedied. On passing from an observation of the dew-point thimble to a reading of the thermometer scale it is necessary to re-focus the observing telescope. This difficulty could be overcome in a number of ways. For example, the telescope could be permanently focussed on the thimble and a suitable lens introduced between the telescope and the movable mirror so as to bring the image of the scale into the same focal plane. It might be necessary to provide means for altering the position of this auxiliary lens as the mirror is moved into different positions relative to the scale. An alternative method would be to employ a binocular arrangement similar to that used in some types of range-finder. The thimble would then be observed through one of the telescopes and the scale through the other, a focussing adjustment being provided on the latter so as to allow of observations on different parts of the temperature scale.

In connection with the distant reading dew-point apparatus (Fig. 10), I would like to suggest that any disturbing temperature effects due to the heat radiation from the tungsten lamp might be eliminated by utilising the reflection of light instead of heat. The polished surface on which dew forms could be introduced into the path of a beam of light (from which heat radiation had been eliminated by suitable filters) in an optical system which forms a sharp image of a convenient object, such as a fine pair of cross-lines. Then, as soon as dew begins to form on the surface the image will become indistinct. Such a modification would not, of course, readily lend itself to adaptation as continuous record method.

Mr. A. H. Davis, M.Sc.: It is interesting to apply the principle of similitude to the case of the ventilated wet and dry bulb-hygrometer. Radiation being negligible in this case, the temperature of the wet bulb falls until the diffusion of heat to the bulb from the warmer incident air just balances the heat loss by evaporation due to the diffusion of water vapour from the bulb into the same air stream.

The table of variables given contains those involved in the convective transfer of heat by a moving fluid,† together with additional quantities necessary to determine the vapour diffusion effect.

This diffusion of water vapour will depend upon its diffusivity D in air, and upon the difference $(m_1 - m_0)$ between the concentration (m_1) of water vapour in the air in contact with the wet bulb and that (m_o) in the air at a distance. Assuming the air in contact with the wet bulb to become saturated with water vapour, then m_1 represents the mass of water vapour necessary to saturate

* An alternative would be to use a fine thread of cotton wool or similar substance instead of the cigarette paper.

† *Cf.* Rayleigh. Nature, XCV., p. 66 (1915).

unit volume of air at a temperature t_w. If L is the latent heat of water at temperature t_w the heat equivalent of the transfer of water vapour will depend upon $L\ (m_1 - m_0)$. This quantity is represented by β in the table below.

Quantity.	Symbol.	Dimensions.			
		Mass.	Length.	Time.	Temp.
Thermal conductivity of the gas	k	1	1	-3	-1
Capacity for heat of gas per unit volume .	c	1	-1	-2	-1
Kinematical viscosity	ν	...	2	-1	...
Diffusivity of water vapour in air.....	D	...	2	-1	...
(Latent heat of water) $\times$ (Excess concentration of water vapour at surface of wet bulb) $= L(m_1 - m_0) =$	β	1	-1	-2	...
Temperature excess dry bulb	$t - t_w$	...	...	...	1
Velocity of air stream	v	...	1	-1	...
Linear dimensions of the body	l	...	1	...	...

Then putting $t - t_w = k^p c^q \nu^r D^s \beta^t w^u l^w$,

we have from dimensions :—

by mass $0 = p + q + t$

length $0 = p - q + 2r - 2s - t + w + u$

time $0 = -3p - 2q - r - s - 2t - u$

temperature $1 = -p - q$.

Whence $p = -1 - p\ ;\ t = 1\ ;\ u = w\ ;\ r = -p - s - u\ ;$

so that $t - t_w = (\beta/c)\ \ (k/c\nu)^p\ \ (D/\nu)^s\ \ (vl/\nu)^u.$

By the kinetic theory of gases there is a numerical relation between the diffusivities* of mass (D), momentum (ν) and energy (k/c). Consequently in the above equation the ratios $k/c\nu$ and D/ν are constants, and the equation becomes

$$(t - t_w) = (\beta/c).\ f(vl/\nu)$$

Here, converting to Principal Skinner's notation, $c = S_\rho \rho$ and β, *i.e.*, $L(m_1 - m_0)$ is readily proved to be $L(p_w - p)\ \rho\sigma/P$, whence a simple re-arrangement gives

$$p = p_w - \frac{PS_p}{L\sigma}.\ (t - t_w).\ f\left(\frac{vl}{\nu}\right)$$

It appears that with the usual laboratory apparatus the wet bulb reading is independent of the velocity of the air for speeds greater than 4 metres per second, and in these circumstances $f(vl/\nu)$ is a constant. Below this speed, however, the reading depends upon the velocity, which should therefore appear in a complete equation. The form of the result implies that the size of the apparatus may have an influence at speeds less than 4 metres per second.

Dr. Guy Barr (communicated remarks) :

Use of Diluted Sulphuric Acid for Standardisation.

The suggestion is frequently made that, since the relative humidity above a dilute sulphuric acid mixture varies only slightly with the temperature, it is unnecessary to take any precautions to keep the temperature constant—*e.g.*, in standardising hair hygrometers. In the absence of efficient stirring the lag in the attainment of equilibrium is, however, so considerable that large errors may be made in this procedure. For example, the air in a closed bell-jar over pure water rarely attains a relative humidity of more than 90 per cent., unless the whole is thermally well insulated. Dr. Griffiths mentions that it is necessary to filter air bubbled through acid mixtures in order to remove spray ; it is, perhaps, not generally known that the air above concentrated sulphuric acid is acid to litmus, even in the absence of spray. Regnault's data, when calculated to relative humidities and plotted against concentration of sulphuric acid, do not lie very well on any smooth curve. In view of the fact that each of his mixtures contained acid and water

* Maxwell, Ency. Brit., 9th Ed., Article " Diffusion."

in fairly simple molar ratios, and of the evidence for the existence of hydrates which is afforded by other physical properties, it appears somewhat arbitrary to use a smoothed curve for interpolation of round values of relative humidity. It is safer, in the absence of equally reliable measurements for intermediate concentrations, to use the same strengths of acid as were employed by Regnault.

Hair Hygrometers.

The effect of exposure to low humidities is noted in Dr. Griffith's paper; it has been the experience of some workers that prolonged exposure to very high humidities causes a similar change in zero. Apropos of Sir Napier Shaw's suggestion that other substances might be used in place of hair, I may mention a Paper by Crockatt and Forster (*J.S.C.*, I., 1919, XXXVIII., 95), in which the behaviour of Chardonnet silk is described. Artificial silks of various kinds have been examined at the N.P.L. by Miss Hadfield, and found to be fairly satisfactory at 40 to 60 per cent. relative humidity. In drier atmospheres the contractions become unduly small for convenient measurement, and above 66 per cent. the stretching is apparently continuous, and requires several days for recovery.

Absorption Hygrometers.

I suggest that, for use at ordinary temperatures, the apparatus designed by Tyndall and Mayo for cold store work would be more convenient if the phosphorus pentoxide were replaced by water; not only is the manipulation simplified, but the heat absorption on evaporation of water is less than the evolution due to combination with P_2O_5, an advantage of some importance when the quantity of moisture in the air is large. In a cold store the plunger might be filled with snow, but it would appear to be essential at these low temperatures (say 50°C. below the body temperature) that a compensation tube should be used, which should be handled in precisely the same manner as the absorption tube; a temperature rise of only 0·7°C. is sufficient to neutralise the whole of the absorption effect from fully saturated air at —10°C. The change in volume due to motion of the oil in the U-tube is not negligible, and should be allowed for in the calculation of the constant.

In this connection, reference may be made to the absorption hygrometer devised by Rideal and Hannah (*Analyst*, 1915, 48), in which the effect of adsorbed moisture on the walls is satisfactorily avoided by measuring the dried gas, not in the original burette over mercury, but over sulphuric acid in the absorption pipette of a simple gas analysis apparatus.

Thermal Effect on Cotton.

In the Paper by Tyndall and Chattock the rises in temperature are stated to be proportional to the vapour pressure. This would be the case so long as the temperature was kept constant, as in the earlier experiments; but when the temperature was varied, as appears to have been the case afterwards, the deflections of the galvanometer would be expected to be proportional to relative humidity, as shown in Dr. Griffith's curve.

Electrical Resistance.

Some results, which I have obtained in endeavouring to use the variation in electrical resistance of cotton as an indication of the hygrometric state, may be of interest. As with other "insulators," it is essential to employ fairly high frequency A.C. in order to avoid polarisation and to keep the current small to avoid warming the cotton. With an ordinary "buzzer" and telephone bridge steady readings were easily obtained. The scoured airship cotton fabric was wrapped on a gilt tube, which formed one electrode, and was covered with a winding of gilt wire, which was the second electrode. The actual value of the resistance depends on the tension used in winding, etc.; but varies to an extraordinary degree with the relative humidity—*e.g.*, in one model it was 850 ohms at 90 per cent. relative humidity, and 780,000 ohms at 33·3 per cent. In the calibration curve the log of resistance is plotted against relative humidity, and gives only a small curvature. Agreement within 1 per cent. can be obtained with rising or falling humidity, but the lag is very considerable, and errors of 5 to 10 per cent. may occur if the humidity is varying with any rapidity. The trouble of lag is experienced in all hygrometers which depend on the attainment of equilibrium between a colloid and the air.

Dew-point Method.

Some precautions in the use of this method may be noted in connection with Dr. Griffiths' experiments. The difference of 0·3°C. between the temperature of the ether and of the silver surface corresponds with an error of 2 per cent. in relative humidity near saturation. The figure refers only to the particular apparatus and particular rate of cooling used in his experiment;

an approximate calculation points to an error of only 0·05°C. for a static difference of 10°C. between the ether and the free air in the case of a silver wall, and of some 0·1°C. for a glass wall 0·1 mm. thick. Most of the difference recorded is due, Dr. Griffiths tells me, to lack of stirring of the ether in these experiments, and is not observed when a slow stream of bubbles is used, as recommended later in the Paper, to keep the ether stirred during the disappearance of the dew. A box is of considerable assistance in avoiding disturbances due to the breath and *hands* of the observer, but it must not be too small. The estimate of the weight of a dew film gives the required data for the size of the box; taking 20 c.c. as an average result for the quantity of air which is saturated by the dew on 1 cm.^{2} at 0°C., it appears that a volume of 2 litres is necessary if the results obtained in a box at 0°C. are to be accurate to 1 per cent.

It is obviously desirable to have the temperatures of appearance and of disappearance of dew as close as possible; if, however, the apparatus is very slowly cooled, the precipitation of dew is not readily visible, since the moisture tends to condense in relatively large drops, and neither the formation nor evaporation of these is sharp. With suitable rates of cooling the interval between appearance and disappearance may be reduced to 0·1°C. in ordinary air. Probably the sharpest determination at low temperatures may be obtained by cooling the polished surface in a very small enclosure and removing the enclosure at various temperatures near the dew-point.

Mr. W. H. Withey: The determination of the moisture in a sample of air by passing a known volume through a suitable arrangement of tubes containing powerful dehydrating agents and observing the increase of weight, is a method requiring extreme care in order to secure accurate results, but, with the possible exception of the dew-point method, it is undoubtedly the most accurate method yet available.

In practice, however, it suffers from several objections which prevent its adoption for everyday working conditions, and, especially in those circumstances in which one would most like to employ it. The air in cold storage chambers, for example, contains a very small quantity of water per unit volume and, in order to determine this by an absorption method, it would be necessary to employ very large volumes of air, with the consequent loss of time; and, moreover, the figure so obtained would only represent the amount of water and not its variation over the period in question.

To overcome this objection the method has been modified by taking the sample of air, treating it with a switch drying agent, and noticing the change of volume caused by the removal of the partial pressure due to the water vapour. Such a method was tried by the author, and the experience obtained proved that all such methods, in which a container for the air is used, are liable to very serious errors which render all results obtained by such forms of apparatus open to suspicion.

The apparatus used was a modification of the well-known Haldane apparatus for the rapid estimation of CO_2 in air. The burette was filled with dry mercury and the sample of air collected by lowering the rubber tube. The gas was next passed over in to a cylindrical vessel containing sulphuric acid packed with glass tubes, and the operation repeated until the volume remained constant. It was noted that, after the first transference, the volume rapidly diminished and that, after six, the succeeding decreases became very small.

There is little doubt that one to three transferences of the gas would suffice to dry the air, and that the small changes subsequently recorded must be attributed to the moistures given up by the glass bulb, and was not complete for hours. The apparatus is, as regards measuring a change of volume, one of great convenience in speed and accuracy. The graduated portion of the burette contained 600 divisions, each corresponding to 1/2,000 of the whole volume, and it was easily possible to read to 1/10 of each division corresponding to an accuracy of 0·005 per cent., but, owing to this defect of the glass, the apparatus was not suitable. A modification was tried by using water in place of sulphuric acid, and noticing the increase of pressure resulting on complete saturation, but this also proved unsatisfactory, owing to the well-known fact that air in a state of complete saturation is almost impossible to obtain.

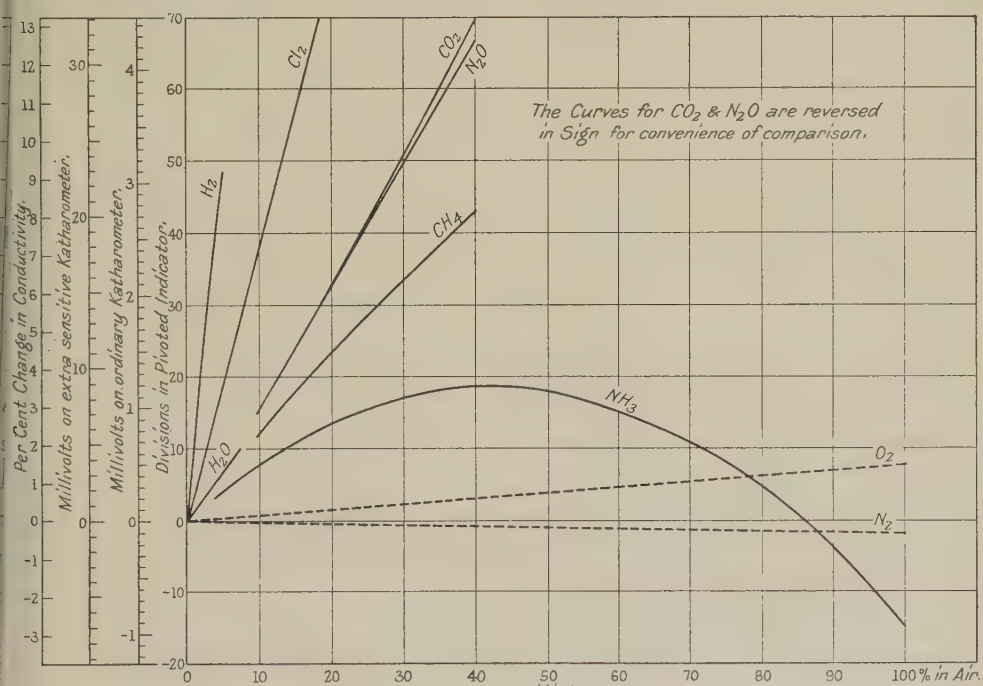
It might be of interest to determine whether the substitution of a silica vessel would overcome the difficulty of condensation. If such proved to be the case, the apparatus would be of great service, and would allow of a rapid determination of the moisture.

Dr. G. A. Shakespear said that in the brief time at his disposal he would confine his remarks to the form of hygrometer of which he had had the most practical experience during the last two years—viz., the katharometer. As the katharometer had been described at a previous meeting of the Physical Society (Proc. Phys. Soc. Lond., 1921, Vol. XXXIII., p. 163) he needed only to give a short summary of the construction and mode of action of the instrument. When the katharo-

neter was fitted up in the usual form of a Wheatstone bridge, the galvanometer of the bridge ould be made to read directly (for a given barometric pressure) the pressure of water vapour t the atmosphere, and by means of a recording galvanometer (such as a thread recorder) a con- nuous record of the absolute humidity could be obtained. It is important to note that the dications of the instrument are a measure of absolute and not relative humidity. The instru- ment worked over a wide range of temperatures—he had used it from —11°C. to about 30°C.— nd was applicable in a variety of circumstances. Dr. H. A. Daynes would give the meeting ome data from which the capabilities of the katharometer might be judged.

Dr. H. A. Daynes: It has been recognised for a long time that the katharometer might be used, if required, as a hygrometer, and a specially sensitive type has been developed for this type of work. It is not until very recently that we have considered the possibility of its use in industry as well as in the laboratory. In particular its use at low temperatures has not received a great deal of attention. We are therefore not in a position to give any considered judgment on its reliability under these more extreme conditions.

Some numerical data are available to show the order of quantities to be dealt with. These



Calibration of Katharometer with Various Gases.

are shown in a graph, which gives very roughly the changes of conductivity and E.M.F.'s involved in the measurement of certain gases, including water vapour, when mixed with air.

If the katharometer is to be useful in cold storage we must consider the case of —10°C. The saturation pressure of water vapour is here about 0·25 per cent. of the total pressure. This changes the conductivity about 1 part in 1,000. If this is to be read to 1 per cent. relative humidity it is necessary to measure the conductivity to 10 parts in a million.

There is no difficulty in making the katharometer sensitive enough, with a suspended pointer galvanometer to show changes of 2 parts in a million. Stability of zero is the limiting factor, and there is reason to believe that this can be made sufficiently good.

Work at higher temperatures is very much easier than at low temperatures, because the katharometer gives an indication of actual percentage of water vapour in the air, not relative humidity.

In cases where CO_2 is present a special form of differential katharometer would be used. Both platinum resistances would be exposed to the gas, but in one case gas would have to diffuse into

the sensitive cell through an ante-chamber containing P_2O_5 or water, in which case the indicator would show the absolute humidity or the difference between that quantity and the saturation humidity respectively.

The danger of condensation on the insulation is not as real so it would seem at first sight as the block is kept some four or five degrees above room temperature. The air in it could never, therefore, be saturated except in a rapid fall of temperature. Moreover, the lag with which the block follows a change in temperature is very much greater than the lag with which the composition of the gas in the sensitive cell follows a change of composition of the gas outside.

Dr. G. W. C. Kaye: If any justification were needed for the plea for a more extended study of hygrometry and its measurement, it has surely been provided this evening. Nothing but good can come of the present attempt to bring the subject up to date. Indeed, if this meeting served merely to provide fresh copy for the writers of text-books, it would have justified the efforts of its promoters. At the National Physical Laboratory investigatory work on hygrometry is still going on, and no one has been more surprised than ourselves at the variety of industries which have recently shown a very practical interest in the subject.

It may be recalled that not long ago this question of humidity was of the most vital importance to the State. This was in connection with the artificial seasoning of timber for aircraft purposes during the war—a question to which I have been asked to refer.

It was not long after the commencement of the war that the importance of the new arm of warfare became increasingly manifest and, with the growing appreciation of its utility, the output of aeroplanes was steadily forced up. This is not the place to dwell now on our limited capacity for construction in those early days. That capacity was restricted by several factors, not the least of them being timber. The chief woods used in this country for aeroplanes were walnut and mahogany (for propellers), ash (for fusilages), and spruce (for struts and spars). Such stocks of naturally seasoned highest-grade woods as existed when war broke out soon began to be exhausted, and we were confronted with a heavy problem in attempting to replenish these stocks.

In general, there had always been a prejudice in this country against the artificial seasoning of timber, in spite of its extensive adoption in America for many years. The situation, however, left us no option in the matter, and had to be met vigorously. Enormous orders for timber were placed abroad, and a considerable number of Government-controlled kilns were established throughout the country by the Ministry of Munitions. The kiln-drying was carried out by the Aeronautical Inspection Department. During the latter part of the war it was my privilege to be associated with this work of kiln-drying, and I should like to be allowed to pay tribute to the work of Mr. S. Fitzgerald and his colleagues for the way the gigantic task was tackled.

Roughly speaking, the seasoning of timber consists in reducing the moisture content from, say, 40 or 50 per cent. to a value in equilibrium with the mean atmospheric conditions. This value is of the order of 15 per cent. in this country; in the drier climate of the States the figure is about 8 per cent. The time taken in the natural seasoning of timber is, perhaps, two or three years; in the artificial seasoning, as many weeks. Two classes of kilns were employed, the progressive or Erith kilns, used chiefly for propeller woods, and the compartment (including the Sturtevant) kilns, used chiefly for ash. Spruce requires only conditioning.

In either type of kiln the temperature is gradually raised to a maximum of about 120°F., and then allowed to fall slowly. During this time the air is humidified artificially, being nearly saturated in the early stages and gradually diminished in wetness during the latter half of the process. The reduction in humidity precedes by a few days the reduction in temperature. The whole object is to encourage the timber to give up its excess natural moisture, but to give it up at the right rate. If the conditions are not right for the particular thicknesses of timber in the kiln, or if things are hurried, the timber will develop cracks, or case-harden, or the physical and structural properties will be impaired.

The temperature and humidity of the air in the kilns were indicated by recording long-arm metal-strip hygrometers of the wet and dry bulb type. The thermometer bulbs were mounted in pockets in the walls of the kilns. It is true that they were sheltered from moving air but, on the other hand, they were protected against moving workmen. It may be added that, while the maximum temperature of the dry bulb was about 120°F., that of the wet bulb was about 110°F.

One of the main difficulties of the work was the lack of skilled and intelligent labour to control the kilns so as to ensure that the somewhat complicated conditions of temperature and humidity were followed. The device was adopted (at any rate with the compartment kiln) of providing a series of process charts for the hygrometers. On these charts were two graphs, one for the dry bulb and the other for the wet, and all the operator had to do was to adjust the dampers

of the kiln so that the two recording pens did not stray from their appointed paths during the two or three weeks of the operation. The travelling inspector could then tell at a glance whether his instructions had been duly carried out.

There is no doubt a very welcome latitude in timber drying, there is also a certain ambiguity in the readings of self-recording wet and dry bulb thermometers but, thanks to the care and devotion of the staff, the empirical paths of temperature and humidity laid down were religiously followed and, once we got the system established, we rarely had a failure. At the time of the Armistice, many millions of feet of air-craft timber had been kiln-dried successfully, and a popular superstition exploded as to the inherently unsatisfactory nature of artificially dried timber.

It was a source of great satisfaction to us to learn from an International Conference in London, and from a visit I paid to the States in 1918, that in the results of our methods of kiln-drying we need not fear comparison with those obtained by any other country. Had this work continued, we should doubtless have taken steps to increase the precision of the hygrometric measurements, but what I have said will perhaps serve as an illustration of the industrial value of hygrometry, if only of a somewhat rough and ready kind.

One further small suggestion as to humidity measurements. The sparking potential between point electrodes is very sensitive to the humidity of the surrounding gas and there might be more than a passing interest in ascertaining whether an hygrometer could be usefully developed on such a basis.

Mr. F. J. W. Whipple: In quoting the formula of Apjohn and August it has been assumed that it is a correct representation of the facts of the case, *i.e.*, that a certain amount of air loses heat to the wet bulb and is saturated in the process, whilst the rest of the air is not affected until this cooled and saturated air is mixed with it. The theory of Maxwell for the case of a wet bulb in a still atmosphere and the theory of Taylor for the case of a well-ventilated wet bulb both allow for the gradual diffusion of heat inwards, and of water vapour outwards from the wet bulb. In Taylor's theory this diffusion takes place in the thin layer close to the bulb, where there is stream-line motion. On either theory the success of the Apjohn-August formula is to be ascribed to the fact that the thermometric conductivity of air and the diffusivity of aqueous vapour are approximately equal.

In this connection I should like to be allowed to point out that in Principal Skinner's Paper the notations used in dealing with the theories of Maxwell and Taylor do not bring out the relation between the resulting formulæ. In quoting Maxwell's result Principal Skinner inserts a γ in the denominator of the first term in the bracket, writing $K/\gamma D$ in place of Maxwell's K/D. The justification for this γ must depend on the circumstances for which k, the calorimetric conductivity, and K, the thermometric conductivity, are defined. According to Skinner $k=K\rho S_v$, whereas Maxwell used the relation $k=K\rho S_p$. The latter form seems to represent the facts of the case better. For comparison it is perhaps advisable to omit the last stage of Maxwell's argument and quote his formula in the form—

$$p=p_w-\frac{PS_p}{L\sigma}\left(\frac{k}{D\rho S_p}+\frac{AR}{4\pi CS_p\rho D}\right)(t-t_w)$$

whilst Taylor's formula as quoted by Skinner becomes

$$p=p_w-\frac{PS_p}{L\sigma}\cdot\frac{k}{D\rho S_p}\cdot(t-t_w)$$

When radiation is neglected the two formulæ become identical.

I understand that Taylor has given a more elaborate formula in which allowance is made for the finite thickness of the stream-like flow over the wet bulb, and that he has made experiments which show that with gases other than air, and evaporating liquids other than water, the modification of the Apjohn-August formula is fully justified.

Replies to Discussion.

Principal Skinner (communicated reply): Mr. Whipple uses the words "whereas Maxwell used the relation $k=K\rho S_p$." There is no reason for saying that he did use this relation. At the very end of Maxwell's Heat, in the appendix, he writes "K of air 0·256 square centimetres per second" as the "rate of propagation of thermal effects in still air." I obtained this from the calorimetric conductivity 0·0000558 by the formula $k=K\rho S$. Furthermore Maxwell in his

article on Diffusion says the quantity which he writes K/D " is certainly less than unity and probably about 0·77." This would make D equal to 0·33 or something less. Now D has a value from experiment of 0·23 approximately if we allow the temperature to be 15°C. Then the value of $K/\gamma D$ is 0·79, much nearer to Maxwell's approximate value than 0·256/0·23 or 1·1.

On the other hand we may discuss the point from general considerations. If the air is still it appears we must use S_v, since the specific heat S_p contains not only the heat required for raising the temperature, but also the heat required to expand the gas. If a process of expansion were going on it is difficult to conceive the meaning of " still."

Dr. Ezer Griffiths (in communicated reply to the enquiry of Mr. W. J. Hall) stated that he had not studied that aspect of the problem. In his method of employing the " thermal effect on cotton hygrometer," changes in the absorptive power would have no influence on the results, as the instrument was calibrated each time it was used.

Dr. A. M. Tyndall, (communicated) : In reply to Dr. Barr, we only experimented with phosphorus pentoxide in the plunger. It is quite true that in general the effect of the change in volume due to the motion of oil in the capillary tube is not negligible, because it is only a small change in pressure that one is measuring. The readings quoted in the Paper were taken with an instrument in which the error due to its neglect was about 1·5 per cent. Dr. Barr is quite right in pointing out that, in the instrument as made up for demonstration at the Meeting, the correction was considerably greater and must be taken into account ; the text is therefore somewhat misleading on this point. I regret that I was unaware of the publication of the work of Rideal and Hannah in the " Analyst," and have not seen their Paper.

In the experiments in which the temperature varied, there is no disagreement between Dr. Griffiths' results and ours. It is the ratio of two deflections for C and B (both of which are affected by the temperature) that is plotted in Curve I. with the vapour pressure of C. The ratio is unaffected by a change in the " constant " of the Paper, due to temperature or to any other cause, though the constant itself changed considerably during the set of readings detailed in Table V.

LIST OF EXHIBITS.

The meeting was preceded by Demonstrations and an Exhibition of Apparatus in the Astrophysics Laboratory, Imperial College of Science. The exhibits included the following :—

1. Apparatus illustrating the History of Hygrometry. From the Science Museum (by courtesy of Col. H. G. LYONS, F.R.S.).

2. Apparatus used in Hygrometry for Meteorological purposes. From the Meteorological Office (by courtesy of Sir NAPIER SHAW, F.R.S.).
   (1) Alluard Condensation Hygrometer (Symons's Meteorological Magazine, XIII., p. 55).
   (2) Lloyd's Hygrodeik.
   (3) Assmann Psychrometer (M.O. Observer's Handbook, 1921, p. 102).
   (4) Comin Psychrometer.
   (5) Aeroplane Psychrometer.
   (6) Model of U.S. Whirled Psychrometer (U.S. Dept. of Agriculture Weather Bureau. Psychrometric Tables, Part I., Washington, 1918).
   (7) Lambrecht's Polymeter (Hair Hygrometer).
   (8) Klinkerfues Hair Hygrometer.
   (9) Richard Hair Hygrograph.
   (10) Dines' Kite Meteorograph (M.O. 202. "The Free Atmosphere in the Region of the British Isles," p. 23. W. H. Dines).
   (11) Dines' Baloon Meteorograph, *ibid.*, p. 29.
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   (B) Ventilated Wet-and-Dry-Bulb Hygrometer (Section 3).
   (C) Dew-point Apparatus (Section 4).
   (D) Wall-fixture Dew-point Apparatus (Section 4c (i)).
   (E) Portable Tube Dew-point Apparatus (Section 4c (ii)).
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